NA-63-1358-13

SERIAL NO. 2

6

DEVELOPMENT OF HIGH, STRENGTH, LOW DENSITY COMPOSITE MATERIALS FOR SATURN APPLICATIONS

ANNUAL SUMMARY REPORT
1 OCTOBER 1963 TO 31 DECEMBER 1964

CONTROL NO. DCN 1-4-84-00007-01 (1F)
CPB 02-1219-63

CONTRACT NAS8-11108

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MATERIALS AND PRODUCIBILITY

DATE 29 January 1965

NO. OF PAGES i to x + 204

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FOREWORD

This report was prepared by North American Aviation, Inc., Los Angeles Division under Contract No. NAS8-11108, "Development of High Strength, Low Density Composite Materials for SATURN Application," for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Propulsion and Engineering Division, Engineering Materials Branch of the George C. Marshall Space Flight Center with Mr. F. P. LaIacona acting as Project Manager.

ABSTRACT

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Composite materials were developed and evaluated for the shell structure of launch vehicle tanks containing pressurized fluid propellants. "Composite materials" as defined in the program included conventional sandwich concepts as well as the more purely material composites, such as glass fibers in a resin matrix. Composites in the form of sandwiches were compared analytically with a base point composite, honeycomb sandwich with aluminum alloy faces. Criteria used for comparison were weight, compatibility with propellants, availability, and manufacturing producibility. Sandwiches studied had composite faces of high strength filamentary materials, such as glass and steel wires in organic resin or aluminum matrices, or monolithic faces, such as high-strength titanium alloys and steels. Composite facing materials with glass fibers and wires were fabricated and tested to establish fabrication methods and design properties. Honeycomb sandwich cores of aluminum, titanium, glass fabric, and mylar, and corrugations were studied for their efficiency for sandwich stabilization and for thermal insulation of the cryogenic fluids. Honeycomb sandwich configurations were fabricated in small flat panel sections and subjected to strength tests at room temperature, 212 F, -109 F, -320 F, and -423 F. These configurations included sandwiches with both faces filamentary composites, sandwiches with both faces monolithic metals, and sandwiches with one face of each type. Face-to-core joining was accomplished with organic adhesives. Tests conducted evaluated the sandwich panels under edgewise compression loading, the cores and the face-to-core bonds under flatwise tension, the cores under flatwise compression and under shear loading, and the face materials under straight tension.

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INTRODUCTION

The demand for ever-increasing pay load launch capability in space boosters necessitates the development of structures with maximum efficiency which will also meet the mandatory high levels of integrity and reliability. Achievement of maximum efficiency in SATURN tank walls depends largely upon the use of materials with low density in relation to their strength and stiffness. In areas where fluids are contained, additional material requirements of sealing and compatibility with cryogenic liquids and temperatures must be met.

Current configurations for SATURN tanks are based on the use of high strength aluminum alloys, Reference (1). Examination of the candidate materials reveals that there are a number with strength to density or stiffness to density ratios appreciably greater than those of the aluminum alloys. A representative list of the more important of these materials and their critical properties is shown in Table I. The properties of two aluminum alloys which are currently utilized in SATURN tanks also are shown in Table I for comparison.

The titanium, steel and magnesium alloys and the beryllium in Table I can all be procured as sheet or plate and can effectively be utilized in those forms in SATURN tanks walls. Utilization of the high strength fibers and wires, however, can be effected only in some form of composite, in which the filaments are combined with another material which furnishes a continuous matrix for stabilization and loading. A typical composite of this kind is glass fiber reinforced resin.

TABLE I

HIGH STRENGTH MATERIALS

MATERIAL	TENSILE ULTIMATE / DENSITY (IN X 10^3)	ELASTIC MODULUS / DENSITY (IN X 10^5)
ALUMINUM ALLOYS		
2219 T87	620	1000
2014 T6	670	1000
TITANIUM ALLOYS	700 - 1200	900 - 1200
ALLOY STEELS	700 - 1000	950 - 1050
MAGNESIUM ALLOYS	400 - 600	1000 - 1300
BERYLLIUM	1040	6040
STEEL PIANO WIRE	5850	1060
GLASS FIBER	7600	1370 - 1650
BORON FIBER	5000	5500

The efficient utilization of the materials of Table I in SATURN tank walls will, in general, require that they be stabilized in some manner to enable them to resist relatively large axial compression loads without buckling. One efficient method of accomplishing this is by utilizing the materials as two faces of a sandwich construction, joined and stabilized by some type of core, for example honeycomb or corrugations.

A determination of the potential efficiency of the high strength materials in comparison with the current SATURN tank materials would require their evaluation in some representative base point structure. A convenient and meaningful base point configuration for such a comparative study would be the double-faced sandwich construction mentioned above.

Other factors to be taken into consideration in assessing the potential usefulness of the high strength materials are availability, fabricability, and compatibility with the contained propellant fluids. Early system usage of the materials is an objective. It is necessary, therefore, that the materials can be made available in the quantities and sizes required for tank production. Efficient and reliable methods of shaping and joining them into the desired composite configurations should require a minimum of development.

Since the end product is a container for cryogenic or hydrocarbon propellant fluids, it is necessary to consider potential chemical reactions of the fluids with the container materials and the possibility of diffusion of the fluids into or through the materials. Where such phenomena may occur, consideration must be given to methods of sealing the container inner wall.

OBJECTIVE AND SCOPE

The objective of this program was to develop and evaluate composite materials for the shell structures of SATURN tanks containing the following propellant fluids: liquid nitrogen, liquid oxygen, liquid hydrogen, and hydrocarbons. The principal criterion used to select composites for study was a comparison of their unit weight with that of aluminum honeycomb sandwich. Other criteria used in the selection of composites were, availability, fabricability, and compatibility with propellant fluids.

In order to simplify the weight comparison and also to avoid a design configuration study, the composites were studied in the form of simple double face sandwiches. For the purpose of this program, therefore, the term "composite" refers to sandwich constructions as well as to the multiphase composite materials such as glass fiber laminates which may be used as elements of the sandwich.

To accomplish the objective the program was conducted in the following three phases:

1. Literature and Industrial Survey

   A comprehensive survey was made to ascertain the state of the art in potentially applicable composites.

2. Experimental Phase I - Screening Composites

   Various core and facing materials were evaluated for their fabricability and for their suitability as elements of sandwich composites. Utilizing these materials, twelve sandwich composites (three for use with each of the four fluids) were fabricated in flat panel sections and subjected to various screening tests at room temperature.

3. Experimental Phase II - Optimum Composites

Based on the screening study, four optimum composites (one for each fluid) were fabricated in flat panel sections and mechanically tested at five temperatures from -423 F to +212 F.

SUMMARY

LITERATURE AND INDUSTRIAL SURVEY

A survey was conducted to review the status of composite material systems including filamentary materials and sandwich construction.

High strength monolithic steels have been proposed and utilized as sandwich facings in aircraft structure. These have been successfully brazed or adhesively bonded to honeycomb cores or welded or mechanically joined to corrugated cores. Titanium alloys have been proposed as sandwich facings for highly loaded structure, including aircraft and booster tankage. Joining of titanium to honeycomb cores by brazing, adhesive bonding, welding, and solid state diffusion bonded has been attempted. None of these methods of joining titanium is completely satisfactory at present.

High strength glass fibers in a resin matrix have been proposed and utilized in both non-sandwich and adhesively bonded sandwich structures including aircraft and rocket motor tankage.

Other high strength filamentary materials, such as steel wires and recently, boron fibers have been proposed for tanks and other structure. Recent work on the solid state bonding of such filaments in aluminum or titanium matrices may enhance their potential as materials for fluid containment. Very little information was found concerning the application of any composite materials under characteristic SATURN conditions where tank walls are relatively thin due to low internal pressure and the axial compressive stresses are relatively high.

EXPERIMENTAL PHASE I - SCREENING COMPOSITES

Analytical studies indicate that the following materials are more efficient than high strength aluminum as facing materials for flat sandwich panels simulating sections of SATURN tank walls:

High strength titanium alloys

High strength alloy steels

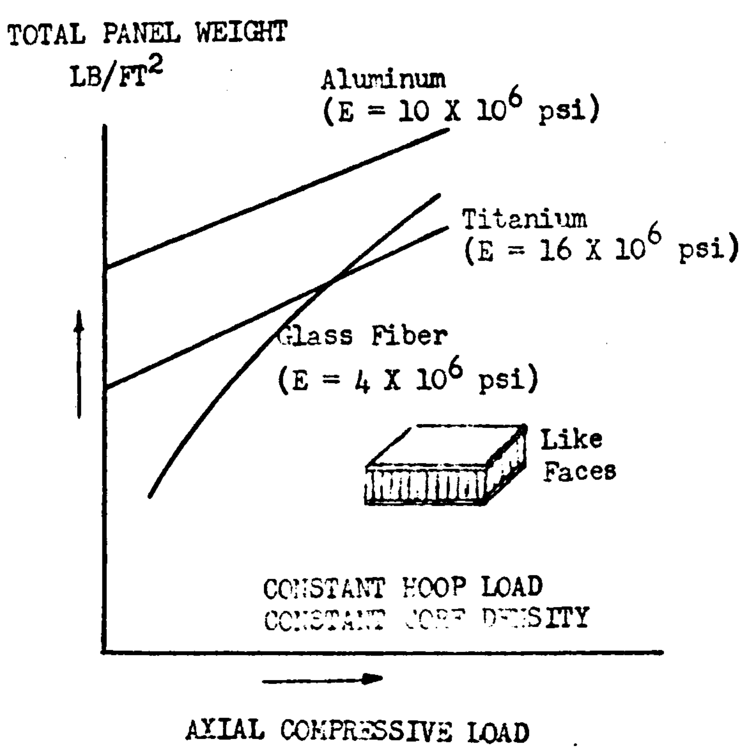
Glass fibers or steel wires in a plastic matrix

Steel wires in an aluminum or titanium matrix

Boron fibers in a plastic or aluminum matrix

Beryllium

Due to decreased core depth and, hence decreased core weight, materials with low elastic modulus, such as glass fibers in plastic, tend to be relatively more efficient with decreasing loads as illustrated in the accompanying figure.



A study indicated that a temperrature difference between the two faces of a sandwich may necessitate increasing facing thicknesses, and hence weight, to eliminate thermal stresses. Choice of face materials with low modulus of elasticity and coefficient of expansion, for example glass fiber, may reduce the thermal stresses without weight penalty.

Several types of filamentary composite facing materials were investigated to obtain fabrication experience and property data. Thin sheets of glass fiber and steel wire, alone or together in a plastic matrix, and steel wire adhesively bonded between aluminum or titanium sheets, were fabricated and tested for tension and compression properties. The results indicated that while it is possible to analytically predict the strength of these materials, considerable work in fabrication and testing will be necessary to obtain reproducible results in tests.

Flat sandwich panels of twelve different configurations were designed for SATURN room temperature conditions, fabricated, and tested at room temperature. Design loads for the panels were as follows:

Ultimate Hoop Tension Load = 10,400 lb/in.

Ultimate Axial Compressive Load = 4000 lb/in

Facing sheets of these panels were of high strength, monolithic titanium alloys or steels, aluminum with embedded wires, glass fiber in plastic, and glass fiber and metal wire together in plastic. Physical investigation of boron and beryllium faces was considered outside the scope of the program. Sandwiches for use with liquid oxygen, liquid nitrogen, or hydrocarbon fuels had low density aluminum or titanium honeycomb core. Sandwiches for use with liquid hydrogen had a duplex core of aluminum and glass honeycomb designed to reduce overall weight by providing both insulation for contained hydrogen and stabilization for the sandwich facings. All face-to-core joining was by adhesive bonding.

Weights of each of the twelve screening composite sandwiches were lower than that of a honeycomb sandwich with 2219-T87 aluminum alloy facings. The percentage weight reductions for the sandwiches with lowest weights in comparison with aluminum sandwich with the same type of core were as follows:

Screening Composite: Outside Face / Inside Face	Weight Reduction (%)
Ti-6Al-4V Ann / Ti-6Al-4V Ann	17
2014 Al + Wire / 2014 Al + Wire	13
Ti-6A-4V HT / 2014 Al + Wire	19
Glass Fiber in Resin / Glass Fiber in Resin	10
Ti-6Al-4V HT / Ti-6Al-4V Ann	16
PH15-7Mo Steel / PH15-7Mo Steel	11
Ti-6Al-4V HT / Ti-6Al-4V HT	25

Tests on the screening composites showed erratic strengths in the face-to-core adhesive bonds, due primarily to inadequate core and face cleaning procedures. The sandwiches exceeded their design load requirements in edgewise compression tests except where low bond strengths at titanium faces caused premature failure and where margin of safety was low in glass and aluminum + wire faces.

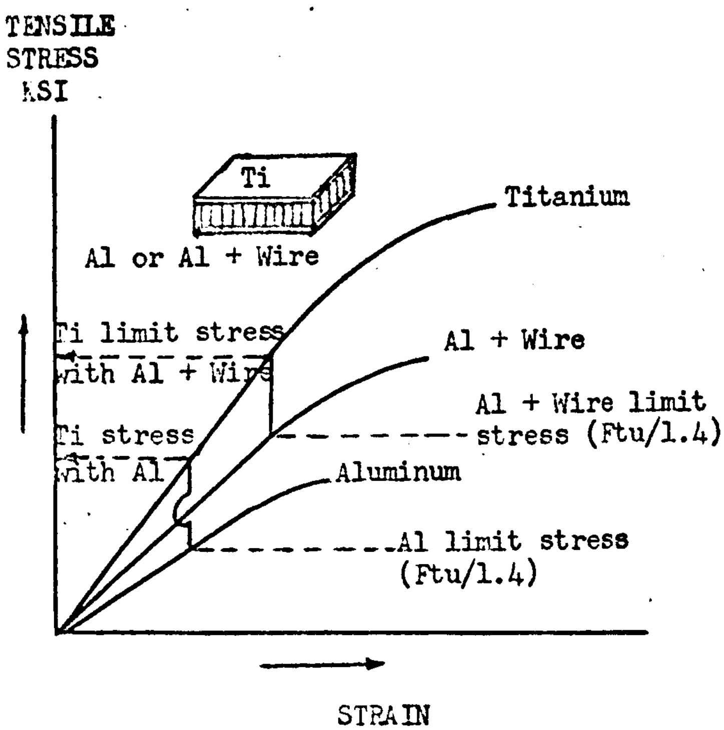
EXPERIMENTAL PHASE II - OPTIMUM COMPOSITES

The following four screening composite sandwich configurations were selected for fabrication and testing as optimum composites at 212 F, R.T., -109 F, -320 F, and -423 F.

Facings	Cores
1. Ti-6Al-4V-Ann (both faces)	Titanium H.C.

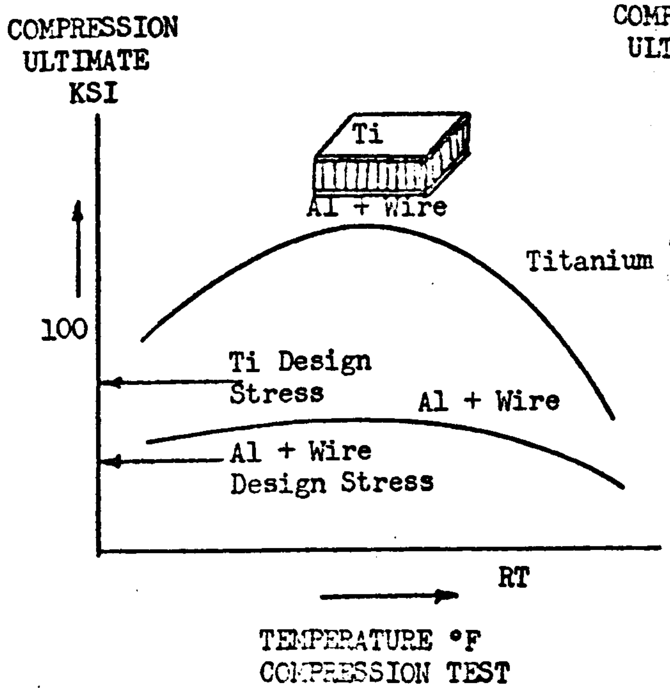
	Facings	Cores
2.	Glass fiber in plastic	Aluminum H.C.
3.	Ti-6Al-4V-HT (outside face) Aluminum + wire (inside face)	Duplex, aluminum HC + glass fabric HC
4.	PH15-7Mo (both faces)	Aluminum H.C.

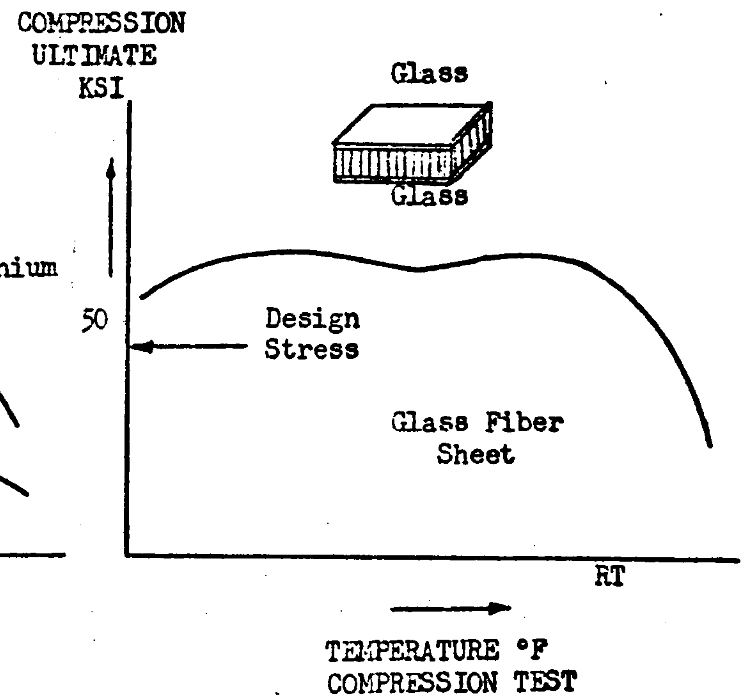
The sandwiches were chosen primarily for their weight advantages. The inside aluminum + wire face of the duplex core sandwich was chosen also for compatibility with the cryogenic fluids. Incorporation of the wire in the aluminum permits the utilization of the titanium at a high tension stress level as illustrated in the accompanying figure.



TENSION TEST

Tests were conducted on the four optimum composites to evaluate face tension strength, core strengths, core-to-face bond strengths and stability under edgewise compression loading. Core-to-face bond strengths were found to be much improved over those obtained in the screening composite tests, due to improved cleaning procedures. The load-carrying ability of the titanium/aluminum + wire, and the glass fiber sandwiches in edgewise compression tended to peak below room temperature as shown in the accompanying figures. The reduction in load carrying ability under compresssion loads at high and low temperatures was considered as probably largely attributable respectively to reduced high temperature strength in the organic bond and





low temperature embrittlement in the bond. The PH15-7Mo sandwich continuously increased in compression strength down to -320, the lowest temperature at which it was tested, due to a very high face to core bond strength.

Tension tests conducted on the glass fiber composite faces showed peak strengths at intermediate temperatures due to deleterious effects of both high and low temperatures on the resin matrix. Tension tests on the aluminum + wire faces showed continuously increasing strength down to -423 F.

LITERATURE AND INDUSTRIAL SURVEY

A literature and industrial survey was initiated to review the status of composite material systems and to provide guidance during the experimental phases of effort. The sources of the required information were:

1. Defense Documentation Center Abstracts
2. NASA Automated Search System
3. Patent Search
4. North American Aviation, In., Space and Information Systems Division (NAA/S&ID)
5. North American Aviation, Inc., Rocketdyne Division
6. Published bibliographies
7. Industrial and Governmental Sources

In addition to these sources, information was obtained from various research and engineering organizations within NAA/LAD.

Defense Documentation Center Abstracts - A search of DDC abstracts was conducted for documents concerned with sandwich, composite materials structures, laminated structures, reinforcing materials, and cryogenics. The search revealed approximately 380 documents in these general areas. A review of the document abstracts indicated that about 30 of the documents relate to the program. These are listed in Reference 2.

NASA Automated Search System - A computer search by this system was conducted for the bibliographic information on composite materials, sandwich structure, and pressure vessels that is contained in the NASA Scientific and Technical Aerospace Reports and AIAA International Aerospace Abstracts. The search revealed approximately 200 documents. These are listed in References 3, 4 and 5.

Patent Search - A search conducted by the NAA Corporate patent files for disclosures on composite materials/structures revealed twenty-four patents on these subjects. None of these was considered closely related to the program.

North American Aviation, Inc., Space and Information Systems Division Discussions were held concerning NAA/S&ID work in related programs. Data was obtained regarding criteria used in the construction of the SATURN S-2 stage. Discussions were held concerning their completed Air Force Programs Contract No. AF 33(600)-43031 on the design, fabrication and testing of wound glass motor cases and contract No. AF 04(611)-8505 on the design and fabrication of titanium tankage, References 6, 7 and 8.

North American Aviation, Inc., Rocketdyne Division - Discussions were held with NAA/Rocketdyne concerning their efforts in the field of composite materials, particularly in the case of glass filament-wound composites.

Published Bibliographies - Several published bibliographies on composite materials available at NAA/LAD, such as Reference 9 and 10 were reviewed for sources of information pertinent to the program.

Industrial and Governmental Sources: Discussions were held with the following industrial sources concerning their efforts in development or application of composite materials for tankage applications.

1. Harvey Aluminum Company, Torrance, California, concerning their current NASA sponsored program to develop a composite material of aluminum and high strength piano wire.
2. Douglas Aircraft Company, Santa Monica, California, concerning their current NASA sponsored program to develop and test lined glass filament-wound tankage of liquid hydrogen containment.

3. General Dynamics/Astronautics, San Diego, California concerning their work on the investigation of composite sandwich structures for the CENTAUR program.
4. U. S. Air Force, Research and Technology Division concerning their work in high strength metals, especially titanium, and in high strength filaments and filamentary composites.
5. U. S. Naval Applied Science Laboratory concerning their work on the compression properties of wound glass filament laminates.
6. U. S. Navy Bureau of Ships concerning their work on high strength monolithic aluminum, steel, and titanium and filamentary glass composite materials for pressure hulls.
7. NASA, Langley Research Center and NASA, Lewis Research Center concerning their work in high strength metallic and non-metallic composite materials.

The principal results of the survey are summarized below. Specific references to data obtained from the survey are made throughout this report.

1. The literature on composites and composite materials was found to be quite voluminous. Many of the numerous documents on the subject that were located had long reference lists or bibliographies. Only a relatively few sources were found, however, that were concerned with the development or application of sandwich composites for conditions similar to those of interest in this program. Many references were concerned with the "micromechanics" of filamentary materials and filamentary composites, or with high temperature composites, subjects that were considered outside the scope of the present program.
2. A number of high strength monolithic metals have been evaluated for

or actually found application as facings for sandwich in highly loaded structures including advanced tankage, References 7, 8, and 11 through 14. Interest has centered chiefly on the high strength aluminum and titanium for tankage applications. A great quantity of data has been generated on the sandwich application of precipation hardening stainless steels, for example in the development of the XB-70 airframe. Almost no information was found on the use of two different materialsused together as the principal load bearing elements in a composite sandwich.

3. Considerable advancement in the state-of-the-art has developed around the design, manufacture and testing of wound glass filamentary composites for primary structure including tankage, References 6 and 15 through 20. Some of these developments have potential applicability to the present SATURN composite program, in particular to (1) the manufacturing and processing techniques associated with tank winding, (2) the properties of the component materials (glass fibers, resins, etc.), and (3) the design and fabrication solutions, characteristic of filamentary composites, that are required for joining, edge attachments and cutouts. Apparently, there have been relatively few studies of wound glass filament composites for compression and buckling situations and even fewer for combined buckling and internal pressure conditions. However, the little work that has been done indicates that very high efficiencies may be obtained.

4. Some development work has been done on composites incorporating steel wire in a resin matrix, Reference 21 and 22. As in the case of glass there has been very little evaluation of compressive properties.

5. Progress in the development of new high strength filamentary materials has proceeded to the point where it can be predicted that some of these will eventually be available for use in hardware. Much of the work in this area has been aimed at high temperature applications Reference 23. However, certain of the filaments, notably boron, alumina, and new glass compositions, promise to be very useful at near room and at cryogenic temperatures. Much of the technology that has been developed for the construction and utilization of glass resin laminates will be applicable to the new fibers.
6. Recently, work has been done in developing composite materials consisting of high strength filaments in metal matrices, References 24 through 27. While none of these materials could be made available in sizes and quantities suitable for use in the present program, some of the compositions, notably steel wire or boron fiber in aluminum or titanium matrices, may have considerable potential for booster tank application. Anticipated advantages of metal matrix composites over resin matrix composites are their relative impermeability to liquids and their adaptability to conventional joining methods, such as welding.
7. The joining of aluminum alloy and glass laminate facing materials to sandwich core has been accomplished principally by adhesive bonding. Precipitation hardening steel facings and cores have been successfully brazed together. Considerable progress has been made in joining titanium faces to high density honeycomb, by solid state diffusion bonding, References 28 and 29. However, the problem of joining of titanium to light low density honeycomb cores of any kind has not yet been satisfactorily solved. Difficulty has been generally experienced.

in obtaining adherence of adhesives to titanium, Reference 6. A number of brazing alloys have been evaluated for use in joining titanium honeycomb sandwich but each has shortcomings, such as excessive fluidity or parent metal embrittlement or corrosive attack. Some work has been done in the joining of dissimilar materials by solid state diffusion bonding, Reference 30.

8. Sandwich facing materials, including monolithic metals and glass fiber laminates, have been evaluated extensively at cryogenic temperatures for mechanical and physical properties Reference 31 through 33. Much less test evaluation has been accomplished on sandwich structures at very low temperatures.

EXPERIMENTAL PHASE I

SCREENING COMPOSITES

ANALYTICAL STUDIES

In order to provide guidance as to what materials and configurations should be fabricated and tested in the screening phase, the following analytical studies were conducted:

Preliminary Weight Comparisons

Axial Load Effects

Honeycomb Core Comparisons

Thermal Gradient Effects

PRELIMINARY WEIGHT COMPARISON

Composite Requirements

While the subject program is not directed toward any specific SATURN components, general requirements must be established in order to assure realistic weight comparisons between different types and arrangements of composites. General assumptions were, therefore, made as to fuel tank pressure, axial load level, and tank size, since each of these parameters has a significant influence on the type, orientation and size of the composite material elements, and the total weight. The core dimensions and weight, for example, are a function of both axial load and shell radius, while the tank wall must be designed for hoop tension, which is a function of internal pressure and shell radius.

Although the program was not directed toward any general parametric studies of variations in loads and shell sizes, applicable analytical formulas were established to provide a basis for a weight comparison of the composites and to indicate the way in which certain parameters influence the weight of the composite elements.

The following requirements, which are representative of SATURN conditions, were established in order to standardize the preliminary weight analysis of composites:

1. Tank Shell Radius = 200 inches.
2. Hoop Ultimate Load = 10,400 lb/in (equivalent to 51.9 psig ultimate tank internal pressure).
3. Axial Ultimate Load = 6000 lb/in.
4. Configurations are uniformly at room temperature.

The following formulas for the calculation of sandwich core depth were derived from Equation (5) of Reference 34. The core depth C is governed by the requirement for general stability in a cylinder under axial compression loading.

For sandwiches with two face sheets of the same material,

$$C = \frac{P_{ult} R}{E\ t} \qquad (1)$$

where

C = core depth

P_{ult} = ultimate compression load/inch

R = tank shell radius

E = face sheet elastic modulus

t = thickness of one face sheet (assuming inner and outer faces are of equal thickness)

For sandwiches with dissimilar face sheets,

$$C = \frac{P_{ult} R}{(E_o\ t_o\ E_i\ t_i)^{1/2}} \qquad (2)$$

The notation is as above except that the subscripts "o" and "i" indicate outer and inner face sheets, respectively.

Comparison with Aluminum Sandwich

A preliminary weight comparison study was made of aluminum honeycomb sandwich and a number of sandwich composite configurations. The results of the study are shown in Figures 1a to 1d. The standard aluminum sandwich is listed followed by the other configurations in order of increasing weights.

Table II identifies the configuration materials and associated properties. The materials are in general a selection from the high strength materials discussed previously (see INTRODUCTION) which at this point in the program appeared available for fabrication and testing. An exception is the boron fiber which is available in very limited quantities only, but is included to show the potential of advanced fibrous materials. Beryllium is included as a matter of interest although its investigation was considered outside the scope of this program due to cost and safety factors.

For the purpose of the weight comparison of Figures 1a to 1d a 3 lb/cu ft core was used in the honeycomb configurations. This was considered to provide for the stabilization of the face sheets and for transfer of internal pressure loads between the sandwich faces. Corrugations were sized to transfer internal pressure loads between faces and to provide stability for the face sheets.

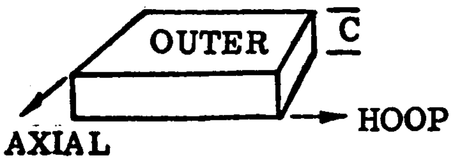
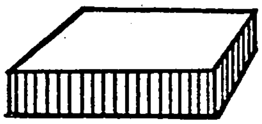
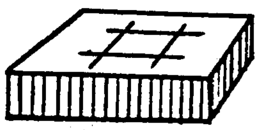
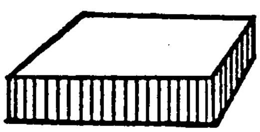
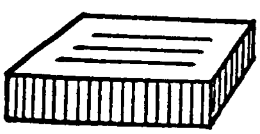
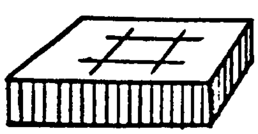
	OUTSIDE FACE	INSIDE FACE	CORE	TOTAL
	LB/FT^2	LB/FT^2	LB/FT^2	LB/FT^2
ALUMINUM 2219-T87  ALUMINUM 2219-T87	1.16 (T = .081)	1.16 (T = .081)	0.36 (C = 1.42)	2.68
BORON IN PLASTIC  BORON IN PLASTIC	0.54 (T = .050)	0.54 (T = .050)	0.30 (C = 1.20)	1.38
BERYLLIUM  BERYLLIUM	0.68 (T = .071)	0.68 (T = .071)	0.09 (C = 0.39)	1.45
BORON IN ALUMINUM  BORON IN ALUMINUM	0.72 (T = .050)	0.72 (T = .050)	0.41 (C = 1.67)	1.85
GLASS FIBER IN PLASTIC  GLASS FIBER IN PLASTIC	0.57 (T = .050)	0.57 (T = .050)	0.90 (C = 3.26)	2.04

FIGURE 1 a PRELIMINARY WEIGHT COMPARISON

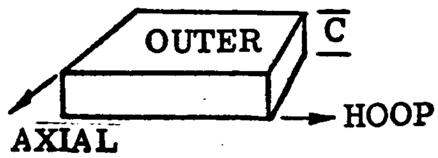
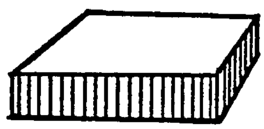
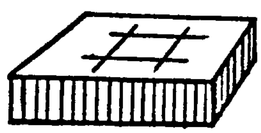
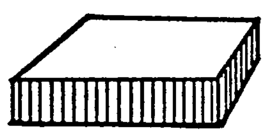
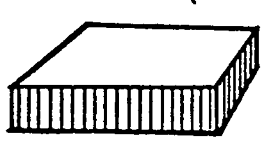
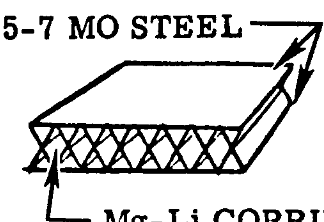
	OUTSIDE FACE LB/FT²	INSIDE FACE LB/FT²	CORE LB/FT²	TOTAL LB/FT²
TITANIUM (HT)  TITANIUM (HT)	0.73 (T = .032)	0.73 (T = .032)	0.58 (C = 2.32)	2.04
GLASS FIBER IN PLASTIC  TITANIUM (HT)	0.63 (T = .055)	0.73 (T = .032)	0.72 (C = 2.90)	2.08
MARAGING STEEL  MARAGING STEEL	0.76 (T = .018)	0.76 (T = .018)	0.59 (C = 2.37)	2.11
TITANIUM (ANN)  TITANIUM (ANN)	0.88 (T = .038)	0.88 (T = .038)	0.47 (C = 1.86)	2.23
PH15-7 MO STEEL  Mg-Li CORRUG.	1.00 (T = .025)	1.00 (T = .025)	0.34 (C = 1.50)	2.34

FIGURE 1 b PRELIMINARY WEIGHT COMPARISON

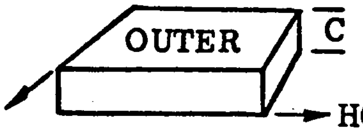
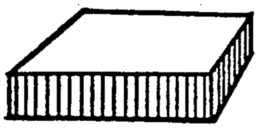
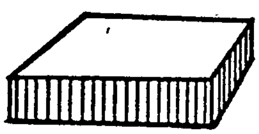
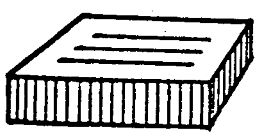
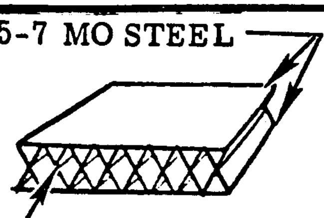
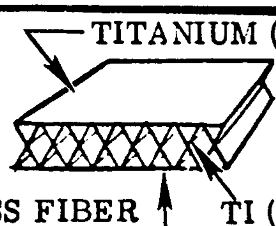
	OUTSIDE FACE LB/FT²	INSIDE FACE LB/FT²	CORE LB/FT²	TOTAL LB/FT²
PH15-7 MO STEEL  PH15-7 MO STEEL	1.00 (T = .025)	1.00 (T = .025)	0.39 (C = 1.55)	2.39
TITANIUM (ANN)  ALUMINUM 2219-T87	1.33 (T = .058)	0.83 (T = .058)	0.29 (C = 1.17)	2.45
ALUMINUM + WIRE  ALUMINUM + WIRE	1.06 (T = .054)	1.06 (T = .054)	0.33 (C = 1.37)	2.45
PH15-7 MO STEEL  ALUM CORRUG	1.00 (T = .025)	1.00 (T = .025)	0.63 (C = 1.50)	2.63
TITANIUM (ANN)  GLASS FIBER IN PLASTIC TI (ANN) CORRUG	0.91 (T = .039)	1.01 (T = .088)	0.77 (C = 1.32)	2.69

FIGURE 1 c PRELIMINARY WEIGHT COMPARISON

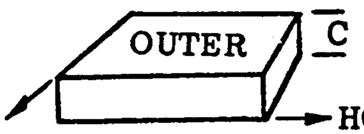
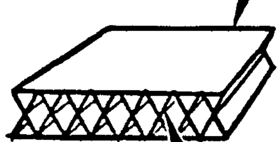
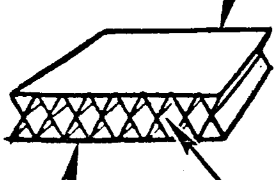
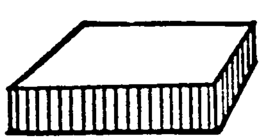
 OUTER, C, HOOP, AXIAL	OUTSIDE FACE	INSIDE FACE	CORE	TOTAL
	LB/FT^2	LB/FT^2	LB/FT^2	LB/FT^2
301 X FH STEEL  301XFH, 301XFH CORRUG.	0.84 (T = .021)	0.84 (T = .021)	1.27 (C = 1.36)	2.95
310 FH STEEL  GLASS FIBER IN PLASTIC, 310 FH CORRUG.	1.07 (T = .026)	1.29 (T = .112)	0.75 (C = 0.95)	3.11
MAGNESIUM LITHIUM  MAGNESIUM LITHIUM	1.92 (T = .272)	1.92 (T = .272)	0.05 (C = .20)	3.89

FIGURE 1 d PRELIMINARY WEIGHT COMPARISON

TABLE II

MATERIAL PROPERTIES(1)

Material	Tension Ultimate Strength (ksi) (Hoop)	Compression Yield Strength (ksi) (Axial)	Modulus of Elasticity (10^6 psi)	Density (lb/cu in)
Aluminum (2219-T87)	62	50	10.3	0.102
Aluminum with wire (20%)(2)	160	60	12.0(4)	0.14
Alum with Boron Fiber (20%)(2)	140	60	14.5(4)	0.10
Titanium Ann (Ti-6Al-4V)	130	120	15.8	0.163
Titanium HT (Ti-6Al-4V)	160	145	15.8	0.163
Magnesium Lithium (LA-141)	19	12	6.5	0.049
Beryllium	70	50	43.0	0.067
PH15-7Mo steel	200	190	30.0	0.277
301 XFH steel	240	230	28.0	0.280
310 FH steel	200	170	30.0	0.286
Maraging steel	270	250	27.0	0.289
Wire (piano wire)	585	485	30.0	0.280
Glass Reinforced Plastic(YM31A Glass)(3)	100	100(5)	7.0	0.080
Boron Fiber Reinforced Plastic(3)	100	100(5)	20.0	0.075

(1) Tentative
(2) Volume percentage. All aligned in hoop direction
(3) 60% Fiber volume. 1 to 1 orientation
(4) Mean of hoop and axial
(5) Equal to compression ultimate

In configurations having similar materials in opposing faces, the face sheets are sized to obtain stresses in the hoop direction equal to their material design allowables. However, in configurations with dissimilar face materials (for example, titanium and aluminum), it was necessary to consider strain compatibility in sizing the face sheets. In general, the stresses were limited to values which would not produce permanent set in the lower-yield strength material of a dissimilar material combination. At this preliminary stage, only an approximate analysis of the strain compatibility was considered necessary. It was recognized, however, that a more sophisticated analysis would be required for final selection and design of composites to be fabricated and tested.

The configuration total weights shown in Figures 1a to 1d are obtained from the weights of skin and core alone. No weights are included for joining (for example, braze or adhesive) or for any protective coatings.

Some significant observations can be made from the results of the preliminary weight comparison. A number of configurations appear potentially lighter in weight than the aluminum alloy faced honeycomb sandwich. In general these configurations have faces of materials with higher strength to density than aluminum. Outstanding are configurations containing titanium, glass fiber sheets with or without embedded steel wires, maraging steel, beryllium, and boron fiber sheets. Aluminum with embedded steel wire appears somewhat better than aluminum in this analysis.

It is noted that, in general, the corrugated configurations do not show to advantage when compared with honeycomb configurations having the same face materials. This results, principally from the fact that face sheets with isotropic properties are sized by the 10,000 lb/in hoop load and can alone carry the smaller 6000 lb/in axial load. The axial load-carrying capabilities of the corrugations are therefore not taken advantage of in the present comparison. In design situations where the axial load exceeds the hoop load, configurations with axial corrugations would tend to offer greater relative advantages. Detail design to specified dimensional and loading parameters would be necessary to qualify the gain. The lightest corrugated configurations were obtained with the low density core materials, aluminum and magnesium.

In some sandwich faces a high strength wire or fiber is added to a matrix of aluminum. In these cases the direction of the wire or fiber is such that the matrix supports the axial load and the wire or fiber provides an increment of support for the higher hoop load. It is interesting to note that high modulus fibers, such as boron, when added to the metal in the hoop direction, contribute to axial stability and permit a decrease in core depth, C. This follows from equation (1) above, where E is the geometric mean of the elastic moduli in the hoop and axial directions.

In general, no weight advantage was gained from the use of two unlike faces in a sandwich. Such configurations were, in general, heavier than one with two like faces of the more efficient material, owing to the restriction of strain compatibility (see discussion above). However, a weight advantage may be gained by a sandwich with unlike faces in a case where compatibility with the contained fluid is a consideration. For example, optimum weight may be obtained through use of a sandwich with a high strength titanium outer face and an aluminum inner face in an oxygen tank where the explosion hazard prevents the use of a titanium innerface.

Some interesting relationships are seen between composite weights and material properties when some of the composite weights of Figures 1a to 1d are plotted against the strength/density of the facing materials, as in Figure 2. The total weight of the composite tends to decrease with increasing strength/density in the faces. There are some local inconsistencies in this general tendency, however. The high weights of the composites with aluminum boron and the aluminum wire faces relative to their position on the strength/density axis is due to the fact that the facing thicknesses of these materials were established by their relatively low axial yield strengths (refer to Table II) and consequently full advantage is not taken of their high hoop tensile strength. It can be reasoned from this that these materials would be more efficient in a situation where the hoop load/axial load ratio is greater than the presently assumed one, say 10/4 instead of about 10/6. In such a situation thinner faces could be used and the high tensile strengths of the materials would be more fully utilized.

The composites with beryllium and with glass-plastic resin faces are also atypical, the former having a very low and the latter a very high core weight. Both cases are explainable on the basis of the elastic modulus of the face material. According to equation (1), the core depth, C, is inversely proportional to the elastic modulus, which in the case of beryllium is relatively very high and in the case of the glass-plastic relatively low.

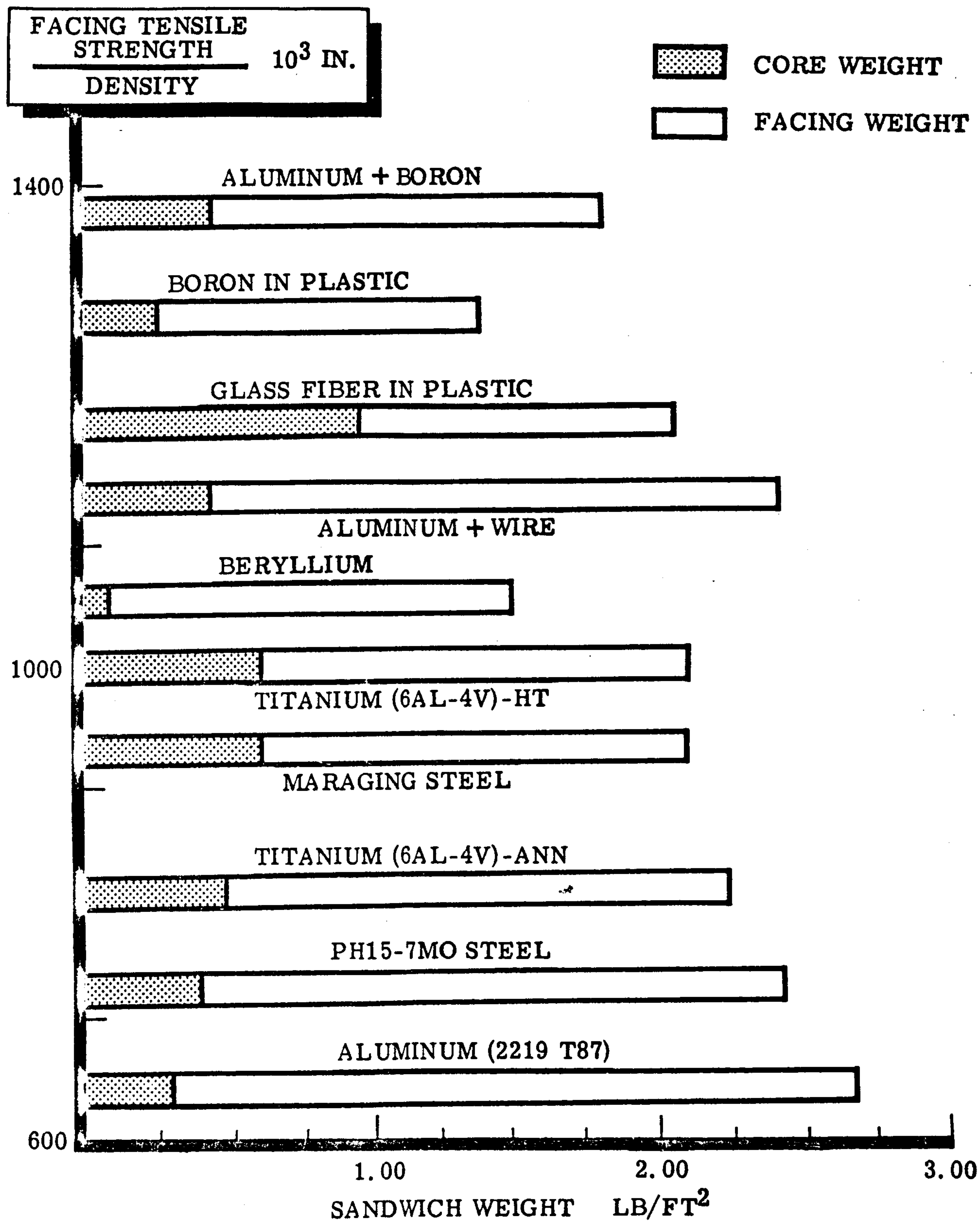


FIGURE 2 SANDWICH WEIGHT ANALYSIS

It is emphasized that the weight figures and comparisons presented in Figures 1a to 2 are based on an approximate analysis and are intended only to indicate what composite configurations and conditions should be further investigated.

AXIAL LOAD EFFECTS

It is seen in Figures 1a to 1d that core weight is a relatively large percentage of the total weight in many of the lightweight configurations. This is due, generally, to the relatively large sandwich thickness, C, required to satisfy equation (1) when axial compression stresses are at a high level. In order to determine the axial load effects, an approximate weight study was made of several of the composites at a constant hoop stress and at various axial compression loads. The results of this study are shown in Figure 3. The material properties used for this study are those listed in Table II, except in the case of the glass fiber-plastic sheet for which the estimated values listed below were used:

Tension Ultimate Strength	230 ksi
Compression Yield Strength	130 ksi
Elastic Modulus	
S-994 Glass	$7(10)^6$ psi
YM31A Glass	$10(10)^6$ psi
Density	0.080 lb/cu. in.

It is noted that the above glass fiber sheet properties are unidirectional, as opposed to the bidirectional properties given in Table II. Other design conditions are those specified for Figures 1a to 1d.

In utilizing the unidirectional properties listed above, fibers were assumed to be oriented in such proportion that the axial and hoop materials exactly satisfy the respective applied load requirements. The strengths and moduli in the hoop and axial directions were taken as fractions of the unidirectional values corresponding to the proportion of fiber. For example, for two independent design conditions of 10,000 lb/in. hoop lead and 5000 lb/in. axial load, the required fiber areas are determined from the loads and allowables as follows:

$$A(\text{Axial}) = \frac{P(\text{axial})}{F_{cy}} = \frac{5000}{130{,}000} = 0.0384 = \text{area of axial fibers}$$

$$A(\text{hoop}) = \frac{P(\text{hoop})}{F_{tu}} = \frac{10{,}000}{230{,}000} = 0.0435 = \text{area of hoop fibers}$$

$$0.0384 + 0.0435 = 0.0819$$

$$\frac{0.0384}{0.0819} + \frac{0.0435}{0.0819} = 0.468\ (\text{axial}) + 0.532\ (\text{hoop}) = 1.000$$

Hence, typical allowable material properties, based on the full face sheet thickness, are:

$$F_{tu}\ (\text{Hoop}) = 230{,}000 \times 0.532 = 122{,}000 \text{ psi}$$

$$F_{cy}\ (\text{Axial}) = 130{,}000 \times 0.468 = 62{,}000 \text{ psi}$$

$$E\ (\text{Hoop}) = 7\ (10)^6 \times 0.532 = 3.7(10)^6 \text{ psi}$$

$$E(\text{Axial}) = 7\ (10)^6 \times 0.468 - 3.3(10)^6 \text{ psi}$$

It should be noted that glass fiber sheet properties derived in this manner have not as yet been verified by test.

It will be seen from Figure 3 that, with decreasing axial load, the weight differences between titanium faced and aluminum faced sandwiches increase slightly and the differences between glass faced and aluminum faced sandwiches increase greatly. These differences are due to differences in sandwich core depth (reflected in core weights) and in face sheet weights, as illustrated by the typical cases below:

TABLE III
HONEYCOMB CORE REQUIREMENTS

Face Sheet Material	Maximum Allowable Cell Size (in)	Minimum Allowable Core Density (lb/cu ft.)		
		Steel Core	Aluminum Core	Mylar Core
Aluminum 2219-T87 ti = to = .081 in.	2.86	1.41	1.09	5.29
Titanium 6Al-4V, Ann. ti = to = .038 in.	1.11	2.62	1.98	9.57
Titanium 6Al-4V, HT ti = to = .032 in.	0.44	3.16	2.44	11.80
Glass Fiber (S994) ti = to = .045 in.	0.83	5.66	4.37	15.17

Hoop load = 10,000 lb/in(ult.). Axial load = -6000 lb/in(ult.)
to and ti = Outer and Inner face sheet thickness, respectively.

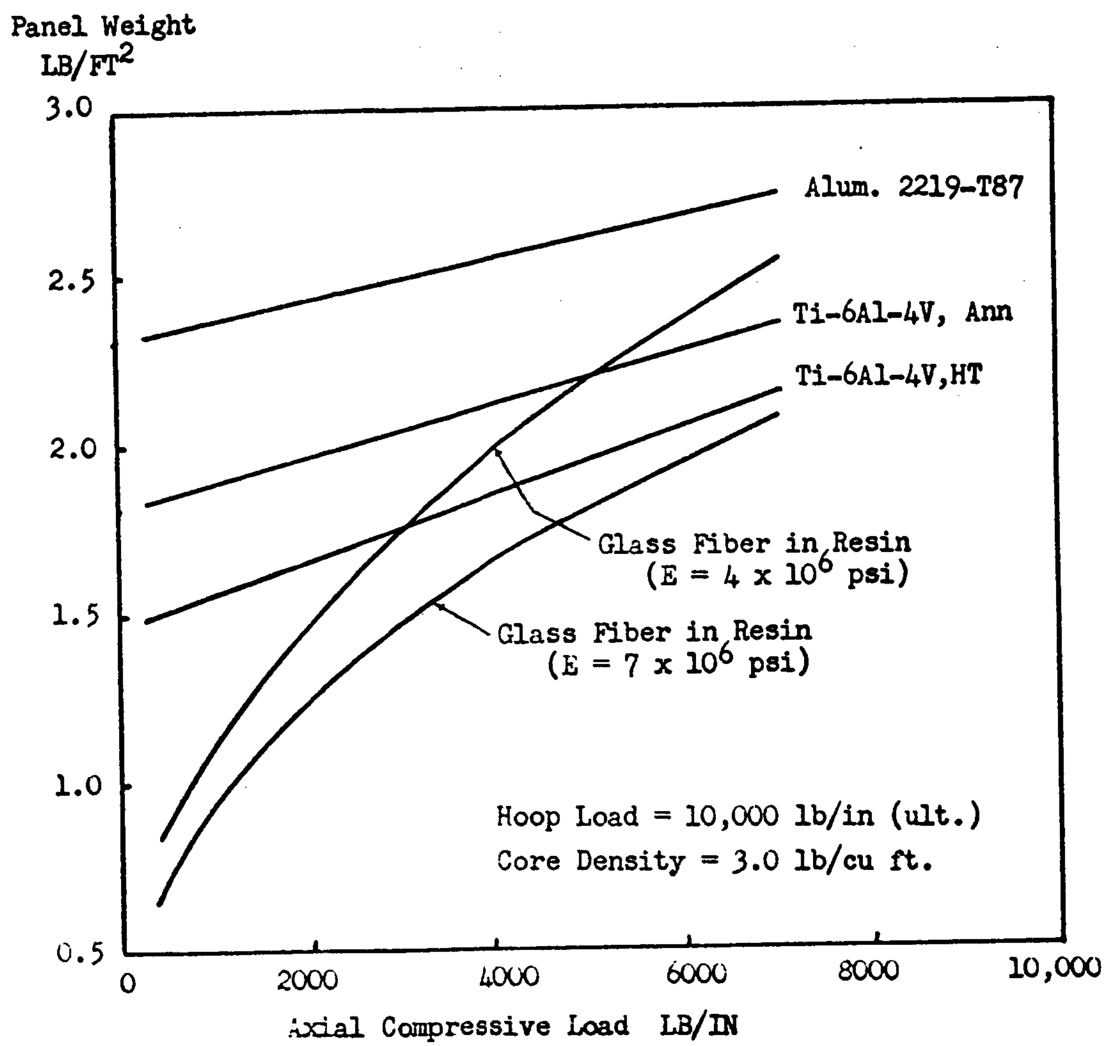


FIGURE 3 AXIAL LOAD EFFECTS

Material	Axial Load (lb/in)	Total Weight (lb/ft^2)	Face Weight (lb/ft^2)	Core Weight (lb/ft^2)	Core Depth (in)
Aluminum	2000	2.44	2.32	0.12	0.57
Aluminum	4000	2.56	2.32	0.24	0.94
Glass Fiber	2000	1.45	0.67	0.78	3.12
Glass Fiber	4000	1.96	0.85	1.11	4.42

With a constant 10,000 lb/in. hoop load, the aluminum face weight is not affected by the axial load variation. However, the glass face weight changes due to the fact that a varying ratio of hoop to axial stress was adjusted by varying the proportions of hoop and axial fibers. The potential for varying the orientation of load-carrying elements is one of the unique features of filamentary composites, such as those under study, and this feature can be used to advantage in optimizing the weight as the above study illustrates.

HONEYCOMB CORE REQUIREMENTS

A study was initiated to help determine what honeycomb core materials and configurations should be investigated in the fabrication and testing phases. The problem of what sandwich core would provide stability for a large cylindrical shape, such as the SATURN tanks, was considered beyond the scope of this program. However, it was necessary to provide a core which would efficiently prevent local instability failure in small scale sandwich compression tests.

Table III shows the results of an analysis performed on three core materials to determine what core configurations would be required to suppress local instabilities in three different sandwich facing materials.

The theoretical equations used for calculating core cell sizes and densities are given in Appendix A. It is noted that these equations are empirical and have not as yet been demonstrated to hold for glass fiber faces. Metallic material properties are taken from Table II. Glass fiber face sheet properties were derived by the method discussed under Axial load effects. Properties of mylar were obtained from Reference 35.

The results shown in Table III indicate that the 3 lb/cu ft. core, which has been assumed so far in this study to provide general stability, will also provide local stability for aluminum and titanium.

However, for the load conditions studied, glass fiber faces would require a core density greater than 3 lb/cu ft. Mylar core of density greater than 3 lb/cu ft would be required for all the facings. This results from the lower elastic modulus of this plastic material as compared with the metal core materials.

Mylar core was included in the study because of its potential use for cryogenic insulation. Current insulation systems for liquid hydrogen tanks incorporate mylar honeycomb core because of the insulative qualities of mylar and its low permeability to hydrogen and other fluids. Cryogenic insulation with mylar core as currently utilized carries no structural loads and, if placed on the outside of the tank, is easily damaged. If mylar core was placed between sandwich faces, it could perform the double duty of insulation and sandwich stabilization and would not be susceptible to damage. More importantly from the standpoint of the present program, such design could possibly effect a worthwhile weight savings, since dead weight insulation is eliminated.

Glass fabric is also effective as a thermal insulation barrier, both it and mylar being of the order of one-five hundredth as thermally conductive as aluminum. Thermal conductance tests on sandwiches with aluminum faces and 2.2 lb/cu ft glass fabric honeycomb core, with one face in contact with liquid hydrogen show panel thermal conductances ranging from 0.11 to 2.5 BTU in/ft °F hr., depending on the gas composition and pressure in the core, Reference 36. Target values for thermal conductance in present SATURN external insulation are within this range.

The shear modulus of glass fabric honeycomb core is of the same order of magnitude as that of mylar honeycomb, and, hence, the weight of glass core required for sandwich stabilization would also be greater than that required for the metal cores.

THERMAL GRADIENT EFFECTS

The fact that the sandwich facing materials studied have widely different thermal expansion and elastic characteristics suggests that the thermal gradients resulting from contained cryogenic fluids might affect the relative efficiencies of the materials. Accordingly a brief study was performed to determine the effect of thermal gradient on sandwich weights. The conditions assumed for studying the effects of such stresses were as follows:

1. Outside Wall = 0°F. (The ambient temperature of the outside wall remains unchanged).

2. Inside Wall = -420°F. (The temperature of the inside wall drops from ambient when filled with a cryogenic liquid).

3. The room temperature properties are used to calculate the effects.

The effects of the conditions were calculated for four of the configurations of Figure 1 which had been assumed to be at a uniform temperature. The equations used for the calculations are given in Appendix B, and the results of the study are summarized in Table IV.

The total stresses shown in Table IV for the sandwich faces are the algebraic sum of the stresses due to imposed loads (hoop or axial) and the thermal stresses. Considerable variation in the magnitudes of the thermal stresses in the "Original Configurations" will be noted. For the configurations with face sheets of the same material and of the same thickness, the thermal stresses are proportional to the product of the modulus, E, and the thermal expansion coefficient, α, and are, therefore, highest for the aluminum sandwich and lowest for the glass sandwich. The magnitudes of the thermal stresses in the configurations with unlike faces are not determinable by any simple rule but are dependent upon modulus, thermal expansion coefficient, and face sheet thickness. In Table IV it will be noted that addition of thermal stresses to load stresses results in total stresses that exceed material allowable stress in the aluminum, titanium, and glass sandwiches but not in the steel-glass sandwich.

Two configurations, the aluminum-aluminum and the glass-glass, were selected for further study to exemplify the effects of the thermal stresses on relative weights, Table V. In the redesigned configurations

TABLE IV

THERMAL GRADIENT EFFECTS
ORIGINAL SANDWICH CONFIGURATIONS

Face Material	Thickness (Inch)	Modulus of Elasticity (10^6psi)	Coeff. of Thermal Expansion (°F)	Direction H (Hoop) A (Axial)	Load Stress (ksi)	Thermal Stress (ksi) ΔT= 420 F	Total Stress (ksi)
Aluminum (Outside)	0.081	10.3	13.3×10^{-6}	H A	+62.0 -37.0	-28.8 -28.8	+33.2 -65.8*
Aluminum (Inside)	0.081	10.3	13.3×10^{-6}	H A	+62.0 -37.0	+28.8 +28.8	+90.8* - 8.2
Titanium HT (Outside)	0.038	15.8	4.7×10^{-6}	H A	+160.0 -62.2	-15.6 -15.6	+144.4 -111.8
Titanium HT (Inside)	0.038	15.8	4.7×10^{-6}	H A	+160.0 -96.2	+15.6 +15.6	+175.6* -80.6
Glass Fiber (Outside)	0.050	7.5	5×10^{-6}	H A	+100.0 -60.0	-7.8 -7.8	+92.8 -67.8
Glass Fiber (Inside)	0.050	7.5	5×10^{-6}	H A	+100.0 -60.0	+7.8 +7.8	+107.8* -52.2
310 FH (Outside)	0.026	300	8×10^{-6}	H A	+200.0 -120.0	-32.6 -32.6	+167.4 -152.6
Glass Fiber (Inside)	0.112	7.5	5×10^{-6}	H A	+46.6 -28.0	+7.6 +7.6	+54.2 -20.4

*Exceeds material design allowable

TABLE V

THERMAL GRADIENT EFFECTS
ORIGINAL VS RESIZED SANDWICH CONFIGURATIONS

Case	Face Material	Thickness (Inch)	Direction H (Hoop) A (Axial)	Thermal Stress (ksi) ΔT=420 F	Total Stress (ksi)	Weights
Original Configuration	Aluminum (Outside)	0.081	H A	-28.8 -28.8	+33.2 -65.8*	Core Depth = 1.42 Face Weight= 2.32 Core Weight= 0.36 2.68 lb/ft^2
	Aluminum (Inside)	0.081	H	+28.8 +28.8	+90.8* - 8.2	
Re-Sized Configuration	Aluminum (Outside)	0.142	H A	-29.6 -29.6	- 5.4 -50.2	Core Depth = 0.86 Face Weight= 4.21 Core Weight= 0.21 4.42 lb/ft^2
	Aluminum (Inside)	0.150	H A	+28.0 +28.0	+62.2 + 7.4	
Original Configuration	Glass Fiber (Outside)	0.050	H A	- 7.8 - 7.8	+92.8 -67.8	Core Depth = 3.26 Face Weight= 1.14 Core Weight= 0.90 2.04 lb/ft^2
	Glass Fiber (Inside)	0.050	H A	+ 7.8 + 7.8	+107.8* -52.2	
Re-Sized Configuration	Glass Fiber (Outside)	0.025	H A	-11.9 -11.9	+84.2 -69.6	Core Depth = 3.61 Face Weight= 1.20 Core Weight= 0.90 2.10 lb/ft^2
	Glass Fiber (Inside)	0.079	H A	+ 3.8 + 3.8	+99.9 -53.9	

* Exceeds Material Design Allowable

in Table V, face sheet thicknesses are adjusted so that total stresses do not exceed material allowables. In the case of the aluminum redesign, total stresses in both face sheets are made to equal material allowables. In the glass configuration redesign, total stresses in one face sheet are less than material allowables due to the fact that an arbitrary restriction was placed on the minimum thickness of glass face that would be used. The aluminum sandwich redesigned to eliminate the harmful effects of the thermal gradient has a much greater weight than the original design. However, the weight of the redesigned glass sandwich is only slightly greater than that of the original design.

The above results indicate that the relative effect of thermal stresses on weight may be quite large in some cases, and that the effects can be strongly influenced by the choice of materials. In general, thermal stresses are minimized by the use of materials, such as the glass laminate, with a low product of elastic modulus and thermal expansion coefficient. Thermal stresses may also be reduced by a proper choice of sandwich face sheets of unlike properties and dimensions.

Redesign of the sandwiches to eliminate entirely the effects of thermal stresses, as was done above, may be considered as a conservative approach. It is emphasized, however, that the present study is only for the purpose of comparing sandwiches of different materials under a specified set of conditions.

FABRICATION AND TESTING OF COMPOSITE SHEET

TYPES INVESTIGATED

Five types of composite filamentary sheets, each in one or more configurations, were fabricated and tested in order to obtain fabrication experience and material property data for the screening studies. The five types are as follows:

1. Wound glass fiber in plastic
2. Wound wire + glass fiber in plastic
3. Aluminum sheet + wire
4. Titanium sheet + wire
5. Wound wire in plastic

A total of 13 sheet configurations were fabricated and are illustrated in Figure 4.

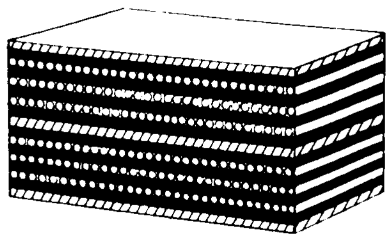
The first three types were ones that showed potential in the preliminary weight comparisons for being more efficient than aluminum alloy as a face material for honeycomb sandwich configuration. The relatively low modulus and high yield strengths of titanium alloys suggests that, on the basis of strain compatibility (refer to ANALYTICAL STUDIES - Preliminary Weight Comparison) a composite of steel wires in a titanium matrix may show efficiency equal to or greater than that of the aluminum and wire composite.

Wound wire-plastic composites were included principally to obtain a comparison of their compression properties with those of glass fiber sheets. The larger diameter of wire and its lower eccentricity as a column compared to glass fibers in a roving suggests that wire may be superior in buckling stability.

Several each of the glass, glass + wire, and wire configurations were made in an attempt to determine the effects of such variables as fiber and wire orientation, layer arrangement, and total thickness on the composite properties.

ALUMINUM OR TITANIUM SHEET
ADHESIVE SHEET (FM 1000 OR FM 1044)
STEEL WIRE
GLASS FILAMENT

METAL (Al OR Ti) - WIRE COMPOSITES



SHEET NO. 1

0.016 IN. ALUM. 7075-T6 CLAD - 3 SHEETS

0.004 IN. DIA STEEL WIRE - 6 PLYS - 192 WIRES/IN./PLY

0.003 IN. FM-1000 ADHESIVE - 8 SHEETS

SHEET NO. 2

0.016 IN. ALUM. 7075-T6 CLAD - 3 SHEETS

0.004 IN. DIA STEEL WIRE - 6 PLYS - 192 WIRES/IN./PLY

0.005 IN. FM-1000 ADHESIVE - 8 SHEETS

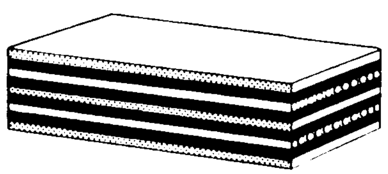
SHEET NO. 3

0.008 Ti-6Al-4V (CHEM-MILLED) - 3 SHEETS

0.004 IN. DIA STEEL WIRE - 6 PLYS - 192 WIRES/IN./PLY

0.005 IN. FM-1000 ADHESIVE - 8 SHEETS

GLASS - WIRE COMPOSITES



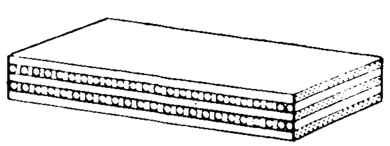
SHEET NO. 4

S-994 GLASS FILAMENT - 3 PLYS - 224 ENDS/IN./PLY

0.004 IN. DIA STEEL WIRE - 2 PLYS - 144 WIRES/IN./PLY

0.005 IN. FM-1000 ADHESIVE - 4 SHEETS

EPON 828/NMA/BDMA RESIN



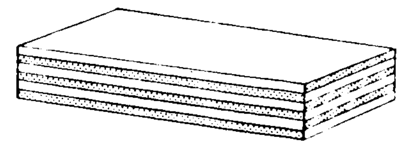
SHEET NO. 5

0.004 IN. DIA STEEL WIRE - 2 PLYS - 144 WIRES/IN./PLY

S-994 GLASS FILAMENT - 3 PLYS - 224 ENDS/IN./PLY

EPON 828/NMA/BDMA RESIN

GLASS COMPOSITES



BIAXIAL ORIENTATION (1:1)

SHEET NO. 6

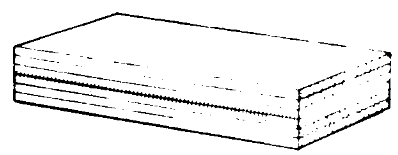
S-994 GLASS FILAMENT - 6 PLYS - 224 ENDS/IN./PLY

EPON 828/NMA/BDMA RESIN - 16% BY WEIGHT

SHEET NO. 7

S-994 GLASS FILAMENT - 6 PLYS - 224 ENDS/IN./PLY

EPON 828/NMA/BDMA RESIN - 26.7% BY WEIGHT



BIAXIAL ORIENTATION (2:1)

SHEET NO. 8

BIAXIAL ORIENTATION (2:1)

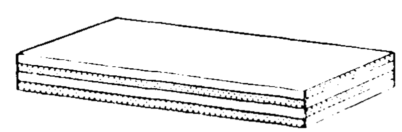
S-994 GLASS FILAMENT - 6 PLYS - 224 ENDS/IN./PLY

EPON 828/NMA/BDMA RESIN - 24.0% BY WEIGHT

SHEET NO. 9

S-994 GLASS FILAMENT - 3 PLYS - 192 ENDS/IN./PLY 2 PLYS - 144 ENDS/IN./PLY

EPON 828/NMA/BDMA RESIN - 20.1% BY WEIGHT

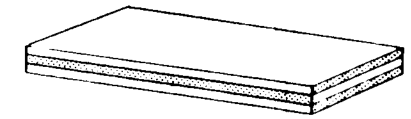


BIAXIAL ORIENTATION (1:1)

SHEET NO. 10

S-994 GLASS FILAMENT - 4 PLYS - 224 ENDS/IN./PLY

EPON 828/NMA/BDMA RESIN - 21.0% BY WEIGHT



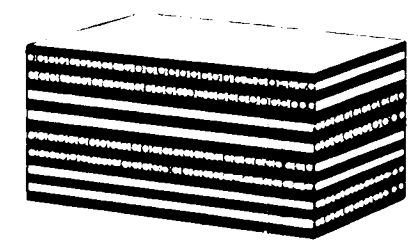
BIAXIAL ORIENTATION (2:1)

SHEET NO. 11

S-994 GLASS FILAMENT - 3 PLYS - 224 ENDS/IN./PLY

EPON 828/NMA/BDMA RESIN - 23.8% BY WEIGHT

WIRE COMPOSITES



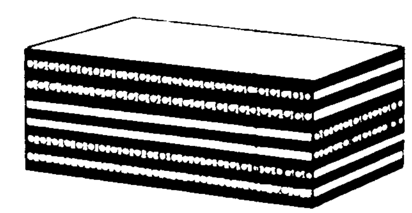
BIAXIAL ORIENTATION (1:1)

SHEET NO. 12

0.004 IN. DIA STEEL WIRE - 8 PLYS - 176 WIRES/IN./PLY

0.002 IN. FM-1044 ADHESIVE - 2 SHEETS (TOP & BOTTOM)

0.001 IN. FM-1044 ADHESIVE - 7 SHEETS



BIAXIAL ORIENTATION (2:1)

SHEET NO. 13

0.004 IN. DIA STEEL WIRE - 6 PLYS - 176 WIRES/IN./PLY

0.002 IN. FM-1044 ADHESIVE - 2 SHEETS (TOP & BOTTOM)

0.001 IN. FM-1044 ADHESIVE - 5 SHEETS

Figure 4 Composite Sheet Configurations

FABRICATION OF COMPOSITE SHEET

Methods of fabrication of composite sheets are briefly described below. Further details of the fabrication processes and equipment given in Appendix C.

Wound Glass Fiber Sheet - Using S-994 glass fibers and Epon 828 resin, six composites sheets were fabricated by filament winding on a flat mandrel, Figure 4. All configurations were bi-axial, either with an equal amount of glass in each direction (1:1 orientation), or with twice as much glass in one direction as the other (2:1 orientation). The composites had a resin content of from about 16 percent to 27 percent by weight (equivalent to about 29% to 52% by volume). The YM31A glass fiber material, which has a higher modulus than S994, was considered for use in the program, but was eliminated because of the potential health hazard from its beryllium content.

Wire + Glass Sheet - This composite was fabricated in a manner similar to that used for the glass fiber composite described above, except that 0.004-inch diameter piano wire was used in place of the glass filaments in one direction, Figure 4. Epon 828 resin was used in winding the glass filaments. Sheets of 0.005-inch FM 1000 adhesive were placed between each layer of wire and glass. The composite was cured under pressure, causing the FM 1000 to flow into and fill the voids between the wires, effecting a good bond between the glass and wire. In one attempt to use only Epon 828 as a matrix, Sheet No. 5, an unsatisfactory bond to the wire was obtained, and the sheet spontaneously delaminated.

Aluminum + Wire Sheet - Means were sought for metallurgically incorporating high strength steel wire in an aluminum matrix. Harvey Aluminum Company, Torrance, California, was contacted to determine the status of their NASA sponsored program, to develop an aluminum-wire composite (see Literature and Industrial Survey). It was learned that material could not be made available from their program in time for investigation in the SATURN composite materials program being conducted by NAA/LAD.

Methods of incorporating high strength fibers and wires in metal matrices are being studied in NAA/LAD internal programs, References 37 and 38. These company funded programs are concerned with the study and development of filamentary composites, and especially with the problem of developing low density efficient matrices for incorporating high strength filaments. It is expected that these internal programs will provide useful information on composite materials for SATURN applications.

In an earlier NAA/LAD program, unsuccessful attempts were made to diffusion bond a wire-aluminum composite by hot rolling wires between bare or zinc coated aluminum sheets at 400° F. The 400°F limitation was imposed to prevent loss of hardness in the wire by removal of cold work. Aluminum sheets and piano wire were eventually successfully bonded together with an organic adhesive. Tests of such composites showed that adhesive shear strengths of about 6000 psi were developed between the wire and aluminum, which is sufficient to break the wire with about a 1/10-inch shear lap.

The adhesive bonding technique was used to fabricate the aluminum + wire composites shown in Figure 4. Three sheets of 0.016 in 7075-T6 aluminum alloy were laminated with two layers of 0.004 inch diameter piano wire. Sheets of 0.003 - 0.005 inch FM-1000 adhesive were placed between each row of wires and between the sheets. The adhesive was cured under pressure, filling the voids between the wires. It was desired to use sheets of aluminum alloys 2014 or 2219 for this laminate, since these alloys are currently used in SATURN construction. However, these were not available at the time these experiments were initiated.

Titanium + Wire Sheet - This composite was made of three sheets of 0.008-inch annealed Titanium-6Al-4V alloy (chemically milled from a heavier gage) laminated with two layers of 0.004-inch diameter piano wire. The make-up and the fabrication procedure for this composite were same as for the aluminum-wire composite, Figure 4.

Wound Wire Sheet - These composites were fabricated in a manner similar to the wound glass, using 0.004-inch diameter music wire. Two biaxial configurations were made, the first with an equal number of wires in each direction (1:1 orientation) and the second with twice as much wire in one direction as in the other (2:1 orientation). Sheets of 0.001-inch thick FM 1044 adhesive separate each layer of wire, with 0.002-inch thick FM 1044 adhesive sheets on the outside surfaces. The composite was cured under pressure, causing the adhesive to flow into and fill the voids between the wires.

TESTING OF COMPOSITE SHEET

Test Methods

Tests were conducted on all of the five types of composite sheets of Figure 4 to obtain tension and compression properties. Considerable experimentation with test methods was necessary, since there are no accepted methods for obtaining properties of fibrous composite materials. The several methods used are described briefly below. Further details on test methods are given in Appendix D.

Tension tests were conducted on 0.75 x 9.5 in. rectangular coupons. The conventional dumbbell-shaped specimen used for tension testing of materials does not readily lend itself to filamentary composite evaluation. The filaments that are cut through in machining the dumbbell shape carry little or no load and, hence, there is not, in effect, a test section of reduced width. In this series of tests, some of the resin matrix specimens and all specimens made with sheets of aluminum or titanium were gripped without end reinforcement. However, after some of the early tests indicated that the test grips were cutting fibers and wires in the resin matrix specimens, asbestos reinforcement pads were adhesive bonded to the ends of the resin matrix specimens in the gripping area.

Composite sheet materials were tested in compression both as conventional coupons and as face sheets of a honeycomb sandwich. Conventional compression coupons were 1 x 3 inch. These were tested in a typical compression test fixture for material coupons, employing "fingers" for lateral support on both sides of the test specimens. Only a few early tests were made with the conventional compression coupons. Literature sources indicated that the interlaminar mode of failure (splitting parallel to the sheet face) was often critical in fibrous composites. Since it was felt that the conventional compression test, in which the coupon is supported from both sides, may suppress the interlaminar mode, the majority of the compression tests were conducted on sandwich coupons. The sandwich coupons were made up of two facings of the composite sheet, each 2 x 4 in., adhesive bonded on each side of a one-inch depth aluminum honeycomb core. A core of high density (20 lb/cu ft) was used to ensure sandwich stabilization. The outer surfaces of the face sheets were unsupported. Compression load is applied to this type of specimen in the direction of the 4-inch dimension. End stability was obtained by filling the ends of the specimen with resin and either clamping metal bars on each side of the specimen at each end or potting an aluminum channel over each end of the specimens (see Appendix D).

Stress strain data and failure stress were recorded for all tests.

Test Results

The results of tension tests on the composite sheets are presented in Table VI. It should be noted that in Table VI and throughout the rest of this report all stress-data on composite sheet are calculated on the total thickness of the composite.

Difficulties were experienced in conducting tension tests on the resin matrix composite sheets. All of the Sheet No. 4 glass-wire specimens, both of the Sheet No. 12 wire specimens, and all but one of the Sheet No. 9 glass specimens failed at or very near areas of stress concentrations, usually at the testing grips. Failures of this type tended to produce scatter and some relatively low values. The incidence of failures in the test grips was greatly reduced, although not eliminated, by bonding asbestos reinforcements in the gripping area. Specimens of

TABLE VI

COMPOSITE SHEET TENSION TESTS

Sheet Type	Sheet No. (1)	Thickness (in.)	Density (lb/in.^{3}) (2)	Test Direction (3)	Tension Strength (ksi) Ultimate	0.2% Yield	Modulus of Elasticity (10^6 psi)	Failure Mode
Al + Wire	1	0.081	0.119	W	135.0		Not measured	
				W	140.0			
				W	136.9			
Al + Wire	2	0.100	0.106	W	106.2	103.4	8.77	Test area failure
				W	106.2	75.1	8.08	
Ti + Wire	3	0.070	0.131	W	126.4		9.35	
				W	135.1	112.8	9.82	
Glass + Wire	4	0.045	0.077	A	121.1		3.03	
		0.045		A	105.6		4.30	
		0.044		A	81.5		4.35	
		0.046		A	85.7	No yielding	3.93	
						or less		
		0.045		W	38.9	than 0.2%	1.15	Failed in grips
		0.046		W	40.7	offset	2.59	
		0.046		W	40.5	observed	2.43	
		0.045		W	42.8	prior to	2.43	
						ultimate		
Glass	8	0.048	0.073	W	138.1	failure	5.43	Test area failure
		0.049		W	139.8		4.72	Test area failure
Glass	9	0.030	0.075	W	103.1		5.07	Failed in grips
				W	136.6		6.00	Failed in grips
				A	99.0		3.95	Test area failure
				A	67.4		3.93	Failed at extensometer pt.
Glass	10	0.030	0.075	-	98.5		4.95	Test area failure

(Continued next page)

TABLE VI (Continued)

COMPOSITE SHEET TENSION TESTS

Sheet Type	Sheet No. (1)	Thickness (in.)	Density ($lb/in.^3$) (2)	Test Direction (3)	Tension Strength (ksi) Ultimate	Tension Strength (ksi) 0.2% Yield	Modulus of Elasticity (10^6 psi)	Failure Mode
Glass	11	0.029	0.073	A	88.0		2.03	Test area failure
		0.030		A	84.4		2.46	Test area failure
		0.030		W	106.1		3.88	Failed near grips
		0.024		W	129.8		4.06	Test area failure
Wire	12	0.032	0.190	-	129.9	No yielding or less than 0.2% offset observed prior to ultimate failure	6.13	Failed in grips
		0.031		-	132.4		6.88	Failed near grips
Wire	13	0.024	0.190	A	83.5		4.40	
				A	102.5		5.39	
		0.023		W	209.3		11.03	Test area failure
		0.029		W	156.9		8.72	

(1) Refers to sheet number in Figure 4
(2) Theoretical density based on nominal compositions.
(3) With or Across direction of wire, or direction of highest glass or wire content, depending on sheet type. (Sheets 10 and 12 each have 1:1 fiber ratio.)

Sheet No. 10 through No. 13, inclusive, have these reinforced ends. Examples of the modes of tension failures in wire and in glass specimens are shown in Figures 27 and 28 in the section FAILURE ANALYSIS. In many of the glass specimens, failure apparently initiated at several points at about the same time, most glass filaments breaking near the center of the area but some breaking near the grips or the reinforcing tabs.

Compression test results on composite sheet materials are given in Table VII. The first two "A" (across the wires) specimens for both the aluminum + wire and the titanium + wire laminates were tested as conventional coupons. All other tests were conducted on honeycomb sandwich coupons with the composite sheets as faces (refer to Test Methods).

Except for the two conventional coupon tests on the aluminum + wire laminate, no 0.2-percent offset yield occurred in any of the faces prior to the ultimate failure. Difficulty was experienced in establishing representative values for ultimate compression strength, due either to the methods used to apply the compression load or possibly to defects in the composite sheet materials. In one test specimen in both the aluminum + wire Sheet No. 2 and titanium + wire Sheet No. 3 failure of the adhesive bond between face sheet and core occurred prior to face sheet failure. In another specimen of each of these materials, failure was initiated by face sheet buckles that occurred adjacent to the metal bars clamped at the specimen ends during application of compression load. Typical failures in the composite face sheets are illustrated in the section FAILURE ANALYSIS.

TABLE VII

COMPOSITE SHEET COMPRESSION TESTS

Sheet Type	Sheet No.(1)	Thickness (in.)	Density (lb/in^3) (2)	Test Direction (3)	Compression Ultimate (ksi)	Compression Modulus (10^6 psi)	Failure Mode
Al-Wire	2	0.100	0.106	A	38.2 29.7(4)	5.50	Local buckling
				A	39.2 31.0(4)	5.20	Local buckling
				A	16.2	5.25	Face-to-core bond failure
				A	31.2 29.1(4)	5.40	Face sheet wrinkling failure
				W	43.0	8.5	Face buckle at grips
Ti-Wire	3	0.070	0.031	A	39.6	5.8	Local face buckling
				A	39.0	6.0	Local face buckling
				A	40.6	5.48	Face buckle at grips
				W	15.4	7.44	Face-to-core bond failure
				W	66.3	—	Local end crippling
Glass-Wire	4	0.045	0.077	A	21.5	4.88	Face-to-core bond failure
		0.045		A	18.9	4.30	Face interlaminar failure
		0.045		W	18.6	4.27	Face interlaminar failure
		0.045		W	27.1	3.93	Face sheet compression failure
Glass	6	0.042	0.078	-	62.1	5.14	Face sheet compression failure
Glass	7	0.055	0.071	-	43.5	4.69	Local end crippling
				-	62.4	3.91	Face sheet compression failure
Glass	8	0.048	0.073	A	39.5	4.24	Face sheet compression failure
		0.048		A	35.2	Undetermined	Face sheet compression failure

(Continued next page)

TABLE VII (Continued)

COMPOSITE SHEET COMPRESSION TESTS

Sheet Type	Sheet No.(1)	Thickness (in.)	Density (lb/in^3) (2)	Test Direction (3)	Compression Ultimate (ksi)	Compression Modulus (10^6 psi)	Failure Mode
Glass	9	0.030	0.075	W	47.2	6.08	Face interlaminar failure
				W	46.0	5.64	Face interlaminar failure
				A	28.7	4.68	Face interlaminar failure
				A	49.9	4.55	Face sheet compression failure
Glass	10	0.028	0.075	-	21.1	6.56	Face interlaminar failure
Wire	12	0.030	0.190	-	39.1	10.0	Either face sheet compression
		0.030		-	26.9	8.87	or face-to-core bond failure
Wire	13	0.022	0.190	A	6.63	Undetermined due to premature failures	Face interlaminar failure
		0.022		A	11.2		Face interlaminar failure
		0.022		W	10.8		Face interlaminar failure

(1) Refers to sheet number in Figure 4
(2) Theoretical density based on nominal compositions.
(3) With or Across direction of wire, or direction of highest glass or wire content, depending on sheet type. (Sheets 6, 7, 10, and 12 each have 1:1 fiber ratio.)
(4) Compression yield strength (0.2% offset). In all other tests, no yielding or less than 0.2% offset was observed prior to ultimate failure.

Analysis of Test Results

The results of the tests on composite sheets are analyzed to determine their relative efficiency and their reproducibility and to correlate their properties with those of their components and with existing data on similar composites.

Metal + Wire Composites:

In Table VIII are shown strength/density ratio values for the metal + wire composite sheets based on test data from Tables VI and VII. Data on the 7075-T6 and Ti-6Al+4V used in the metal + wire laminates are included for comparison. Comparing the tension ultimate/density ratios, it is seen that the addition of wires to the aluminum and titanium alloys significantly increased the tension efficiency. The compression yield efficiencies of the composite sheets are low in comparison to the tension. This is to be expected, since the tests were in the "A" direction (across the wires) and therefore the test values represent only the strengths of the metal sheets. Thus, referring to the data in Figure 4 and in Table VII for sheet No. 2..

Stress in the 7075-T6

$$= \frac{(\text{Stress in composite sheet})\ (\text{Thickness of composite sheet})}{(\text{Thickness of aluminum sheets})}$$

$$= \frac{(29.7\ \text{ksi})\ (0.10\ \text{in})}{(3 \times 0.016\ \text{in})}$$

$$= 61.8\ \text{ksi} \approx \text{Fcy of 7075-T6}$$

The fourth column in Table VIII shows tension ultimates of the metal + wire composite sheets calculated from the properties of the component elements.

TABLE VIII

COMPOSITE SHEET ANALYSIS (1)

METAL + WIRE

Composite Type Sheet No.	Test Direction (2)	Tested Tension Ultimate (ksi)	Calculated Tension Ultimate (ksi)	Tested Tens. Ult./Density (in x 10^3)	Tested Compression Yield (ksi)	Tested Comp. Yld./Density (in x 10^3)
Alum 7075-T6 (Reference)	—	70	—	700	63	630
Alum + Wire 1	W	137	142	1150	—	—
Alum + Wire 2	W A	106 —	118 —	1000 —	— 29.7	— 296
Ti + Wire 3	W	131	166	1000	—	—
Ti-6AL-4V(Ann) (Reference)	—	130	—	810	—	—

(1) Based on data from Tables VI and VII

(2) With or Across direction of wire

The following equation, was used for these calculations:

$$\sigma_c = V_w \sigma_w + V_m \sigma_m \qquad (2)$$

Where

σ_c = Composite ultimate stress

w = Wire ultimate stress

σ_m = matrix ultimate stress

V_w = volume fraction of wire

V_m = volume fraction of matrix

In using Equation 2, it was assumed that the composite adhesive carries no load. Volume fractions of the components are based on the make-up of configurations as shown in Figure 4.

The following example illustrates the use of the above equation: For the aluminum + wire Sheet No. 1

$$\sigma_c = V_w \sigma_w + V_m \sigma_m$$

$$= (.179 \times 585 \text{ ksi}) + (594 \times 70 \text{ ksi}) - 142 \text{ ksi}$$

The tested tension ultimate values are seen to be about 80% and 90% of the calculated values for the titanium composite and the aluminum composite, respectively.

A brief analysis was also conducted to determine if the test stress-strain curves of the aluminum + wire and titanium + wire could be constructed analytically from the stress-strain curves of the composite components. In Figures 5 and 6 are shown the tested tension stress-strain curves, "A" and "B", of the aluminum-wire Sheet No. 2 and titanium-wire Sheet No. 3 in comparison with analytically constructed stress-strain curves. The "C_1" curves, representing the same laminate make-up as the corresponding test curves, were constructed from stress-

Curve Designation		0.2% Yield Strength (ksi)	Modulus of Elasticity (10^6 psi)	Density (lb/in.^{3})	Resin Content (Vol %)
Test*	A	75.1	8.08	0.106	38
	B	103.4	8.77	0.106	38
Constructed	C_1	85.0	8.5	0.106	38
	C_2	120.0	13.3	0.136	11

* Sheet. No. 2 of figure 4

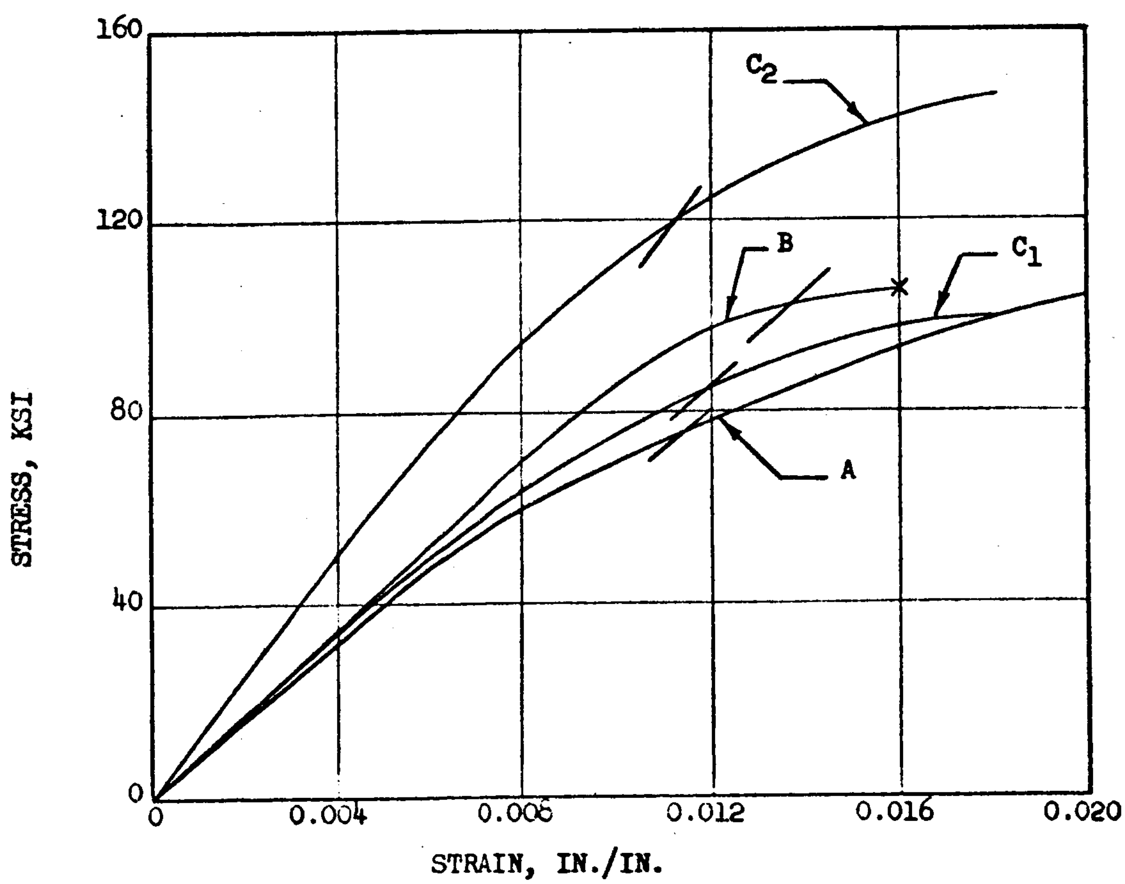


Figure 5 ALUMINUM + WIRE STRESS-STRAIN DATA

Curve Designation		0.2% Yield Strength (ksi)	Modulus of Elasticity (10^6 psi)	Density (lb/in.^{3})	Resin Content (Vol %)
Test*	A	-	9.35	0.131	47
	B	112.8	9.82	0.131	47
Constructed	C_1	110.0	11.4	0.131	47
	C_2	167.0	17.8	0.182	17

* Sheet No. 3 of figure 4

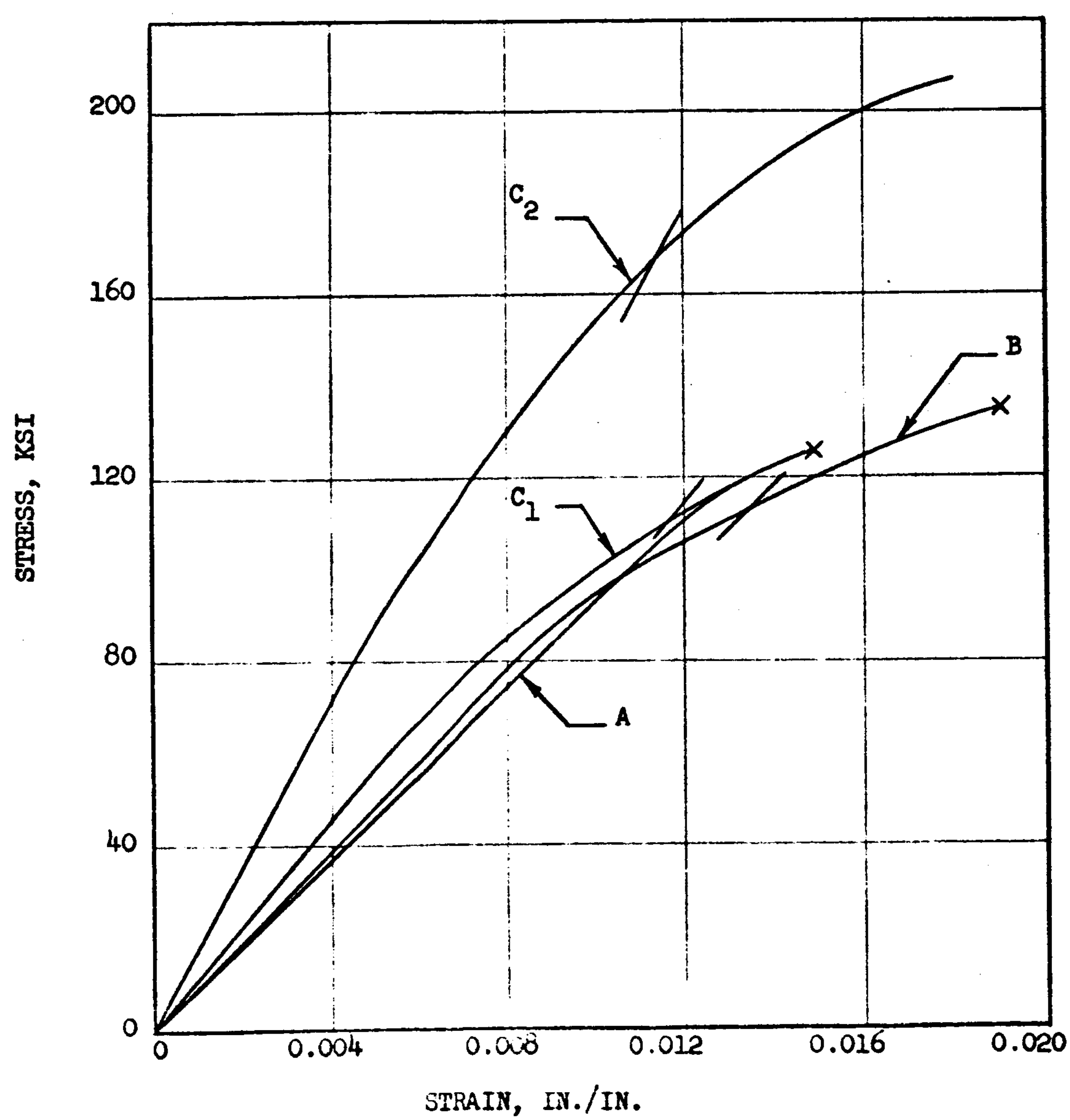


Figure 6 TITANIUM + WIRE STRESS-STRAIN DATA

strain curves of 7075-T6 aluminum alloy and steel music wire in one case and Ti-6Al-4V titanium alloy and steel music wire in the other. The method of constructing the stress-strain curves is presented in Appendix E. It is seen in Figures 5 and 6 that the "C_1" constructed curves are reasonably close to the test curves in both types of laminates. The tested yield strengths also are very close to the calculated yield strengths, if average data are considered.

The test curves and the "C_1" constructed curves in Figures 5 and 6 represent laminates with specific resin contents. Laminates of this type with less resin would be more efficient, since the resin adds to the weight but carries essentially no load. Assuming that the constructed curves are a good approximation of what can be expected from actual materials, it is possible to predict the properties of laminates with lower resin contents. The "C_2" constructed curves in Figures 5 and 6 represent such materials. The yield strength-to-density ratios of the "C_2" hypothetical materials are compared below to those of the aluminum and titanium alloys:

Material	Yield Strength/Density (10^4 in.)
7075-T6 Aluminum	64
"C_2" Aluminum + Wire	88
Ti-6Al-4V Titanium	75
"C_2" Titanium + Wire	92

The above properties are characteristic of the laminates loaded in the direction of the wires.

Glass and/or Wire

In Table IX are shown strength/density values for the glass fiber-composites and the wire composites with plastic resin or adhesive matrices, based on test data from Tables VI and VII. None of the test values was used where "face interlaminar failure" occurred. Values for 2219-T87 aluminum are included for reference, since this material was chosen as the standard of comparison for the program (refer to OBJECTIVE AND SCOPE). Since no yield data were obtained from the composites, a rough measure of their efficiencies in compression is afforded by comparison of their compression ultimates with the compression yield of the aluminum alloy.

It is seen in Table IX that the tension ultimate/density ratio values for all the materials are higher than that of the 2219-T87, except for Panel No. 4 in the direction of the wires. Some of the glass panels show considerably greater tension efficiency than the aluminum alloy. The compression ultimate/density ratios of the glass fiber sheets are equal to or higher than that of the aluminum alloy, and the compression ultimate/density of the glass fiber + wire sheets and the all-wire sheets are lower than that of the aluminum alloy. There is some indication, however, in the results on Sheet 4 that the wires may be beneficial in compression in comparison to glass fibers. In this sheet the ratio of compression ultimate to tensile ultimate is much greater in the wire direction, "W", than in the glass direction "A" (27.9/40.7 vs 21.5/82.5). This may be attributable to the greater buckling stability of the straight metal wires as compared to the glass fibers, which are roughly in a helical form in the rovings used for

TABLE IX

COMPOSITE SHEET ANALYSIS (1)

GLASS AND/OR WIRE

Composite Type Sheet No.	Test Direction (3)	Tested Tension Ultimate (ksi)	Calculated Tension Ultimate (ksi)	Tested Tens.Ult./Density (in x 10^3)	Tested Compression Ultimate (ksi)	Tested Comp. Ult./Density (in x 10^3)
Glass + Wire 4	A W	92.5 40.7	— —	1200 529	21.5 27.9	280 360
Wire 12	—	131	163	690	33	174
Wire 13	W A	183 —	200	960 —	— —	— —
Glass AV 6 and 7	—	—	—	—	62.9	845
Glass 8	W A	139 —	153 —	1820 —	— 37.4	— 500
Glass 9	A	99	77	1320	49.9	656
Glass 10	—	98.5	115	1290	—	—
Glass 11	W A	130 82.2	153 77	1700 1080	— —	— —
Alum 2219 T87 (Reference)	—	60	—	600	50(2)	500(2)

(1) Based on data from Tables VI and VII
(2) Yield or yield/density
(3) With or Across direction of wire, or direction of highest glass or wire content, depending on sheet type.

winding.

In the fourth column in Table IX are shown calculated tension values for the composites. Calculations for the wire composites were based on Equation (2), assuming that only the wire carried any significant load.

Thus for wire Sheet No. 12 where one half the wires are in both the 0° and 90° directions;

$$\sigma_c = V_w \sigma_w + V_m \sigma_m \quad (\sigma_m = 0)$$

$$= .278 \times 585 \text{ ksi} = 163 \text{ ksi}$$

Experience has shown that it is difficult to calculate the properties of glass fiber laminates from the properties of the components because of the variable effect of fabrication processes on the properties of the fibers. The calculated tension values for the glass fiber sheets in Table IX are, therefore based on a nominal value of 230 ksi for unidirectional S994 glass fiber laminates with about 20% by weight resin content, Reference 39. Calculation of the composite strengths is accomplished as described previously under Axial Load Effects

Thus for Sheet No. 11:

"W" Tension Ultimate = Unidirectional Strength X Proportion of fibers in "W" direction

$$= 230 \text{ ksi} \times 2/3 = 153 \text{ ksi}$$

Tested tension data for the wire composite, Sheet Nos. 12 and 13, are from 80% to 90% of the calculated tension values. Tension data for the 2:1 oriented glass-fiber composites, Sheet Nos. 8, 9 and 11 range from about 105% to 130% of calculated values in the direction of one-third the fibers ("A") and from about 85% to 90% in the direction of two-thirds the fibers ("W"). In the 1:1 oriented glass-fiber composite, Sheet No. 10, the test value is about 85% of the calculated value.

The results of the investigation of composite sheet materials indicate, generally, that these materials can be fabricated with reasonably reproducible properties. The amount of scatter obtained in the test values can be expected to diminish with further experience in fabrication and testing, at least for the tension values. Scattered results in compression in the plastic resin composites has been reported by other investigators and appears to be characteristic of these materials in their present form and correlatable with the interlaminar failure mode, Reference 40. Various ways of improving the compression properties have been suggested, such as fibers woven into the sheet in such a manner that they carry some load in the direction normal to the sheet thickness. However, investigation of these methods of improvement is beyond the scope of this project.

Lack of agreement between test and calculated values for the composite sheets may be attributable to testing difficulties in the case of the resin matrix composites. However, failure to obtain 100% of calculated values is not easily explainable for the aluminum + wire and titanium + wire composite sheets. The nature of the failures in these materials indicated that the adhesive bond was intact up to or very close to the time of failure (see FAILURE ANALYSIS). One possible explanation is that the sheet metals and the wires did not reach their ultimate failure loads at the same strain level. For example, the aluminum may have passed the peak of its stress-strain curve and thus may be carrying a diminishing load at the time the wires reached their ultimate load level.

SELECTION OF SCREENING COMPOSITES CONFIGURATIONS

The 12 Screening Composite configurations selected for Phase I fabrication and testing are shown schematically in Figure 7. The upper surface of these configurations represents a tank outer wall. The choice of face sheets for the configurations was based primarily on availability for the present program, structural efficiency in comparison with aluminum, compatibility with the propellants, temperature level and temperature gradient with contained propellants, and fabricability.

The composition and makeup of the composite sheets are shown in Figure 8. The same aluminum + wire laminate was used in three composite configurations. However, it is probable that further study would show that a different laminate make-up would be required to obtain minimum weight in each composite. Further description of the 12 screening composites and the considerations that led to their selection are given in the following sections.

LIQUID	CONFIGURATION		
	I	II	III
LN_2 (LIQUID NITROGEN)	6Al-4V TITANIUM (ANN) Ti HONEYCOMB 6Al-4V TITANIUM (ANN)	ALUMINUM + WIRE LAMINATE ALUMINUM HONEYCOMB ALUMINUM + WIRE LAMINATE	GLASS TAPE + WIRE LAMINATE ALUMINUM HONEYCOMB GLASS TAPE + WIRE LAMINATE
LOX (LIQUID OXYGEN)	6Al-4V TITANIUM (HT) ALUM. HONEYCOMB ALUMINUM + WIRE LAMINATE	GLASS TAPE ALUMINUM HONEYCOMB GLASS TAPE	WOUND GLASS ALUMINUM HONEYCOMB WOUND GLASS
LH_2 (LIQUID HYDROGEN)	WOUND GLASS GLASS H'COMB ALUM. HONEYCOMB ALUM. FOIL 6Al-4V TITANIUM (ANN)	6Al-4V TITANIUM (HT) GLASS H'COMB ALUM. HONEYCOMB ALUM. FOIL 6Al-4V TITANIUM (ANN)	WOUND GLASS GLASS H'COMB ALUMINUM HONEYCOMB ALUM. FOIL ALUMINUM + WIRE LAMINATE
HF (HYDRO-CARBON FUEL)	PH15-7Mo STEEL ALUMINUM HONEYCOMB PH15-7Mo STEEL	MARAGING STEEL ALUMINUM HONEYCOMB WOUND GLASS	6Al-4V TITANIUM (HT) ALUMINUM HONEYCOMB 6Al-4V TITANIUM (HT)

FIGURE 7 SCREENING COMPOSITES

ALUMINUM SHEET

WOUND GLASS FILAMENT OR GLASS TAPE

ADHESIVE SHEET (FM-1044)

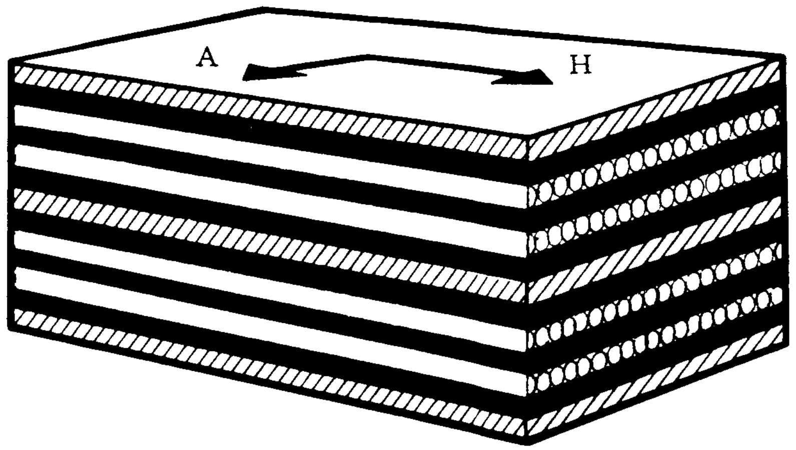
H = HOOP DIRECTION

STEEL WIRE

A = AXIAL DIRECTION

2014 ALUMINUM-WIRE COMPOSITE

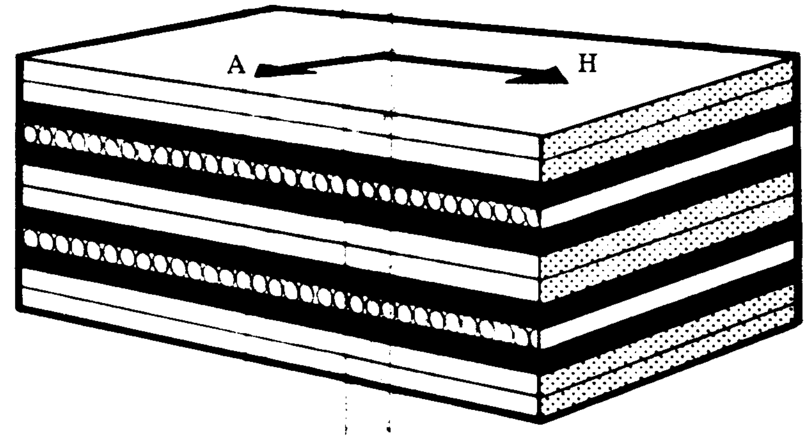
CONFIGURATIONS LN_2 - II, LOX-I, AND LH_2 - III



0.010 IN. 2014-T6 ALUMINUM - 3 SHEETS
0.004 IN. DIA STEEL WIRE - 4 PLYS -
192 WIRES/IN./PLY
FM-1044 ADHESIVE - 6 LAYERS -
0.001 IN./LAYER

GLASS TAPE - WIRE COMPOSITE

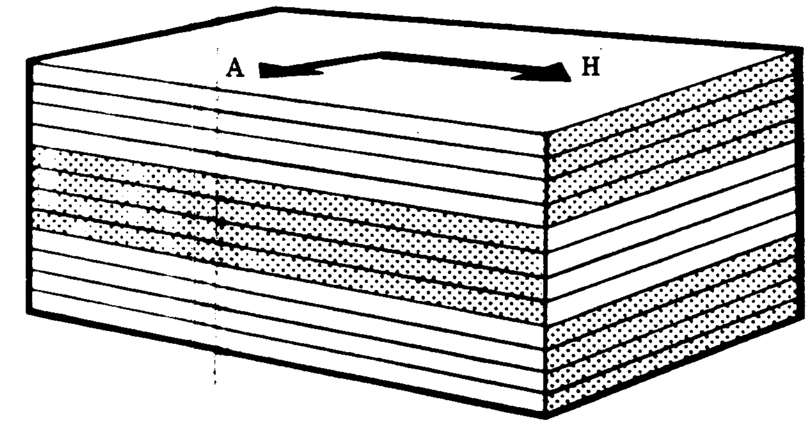
CONFIGURATION LN_2 - III



0.005 IN. STRATOGLASS 660 ST GLASS TAPE - 6 PLYS -
130 ENDS/IN./PLY - 20 PERCENT RESIN BY WEIGHT
0.010 IN. DIA STEEL WIRE - 2 PLYS -
65 ENDS/IN./PLY
FM-1044 ADHESIVE - 2 LAYERS 0.002 IN./LAYER
2 LAYERS 0.003 IN./LAYER

CLASS TAPE COMPOSITE

CONFIGURATION LOX - II

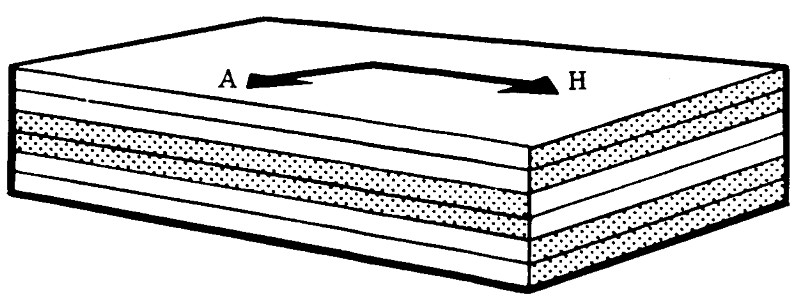


BIAXIAL ORIENTATION (2:1)

0.005 IN. STRATOGLASS 660 ST GLASS TAPE - 12 PLYS -
130 ENDS/IN./PLY - 20 PERCENT RESIN BY WEIGHT

WOUND GLASS COMPOSITE

CONFIGURATIONS LH_2 - I AND HF - II

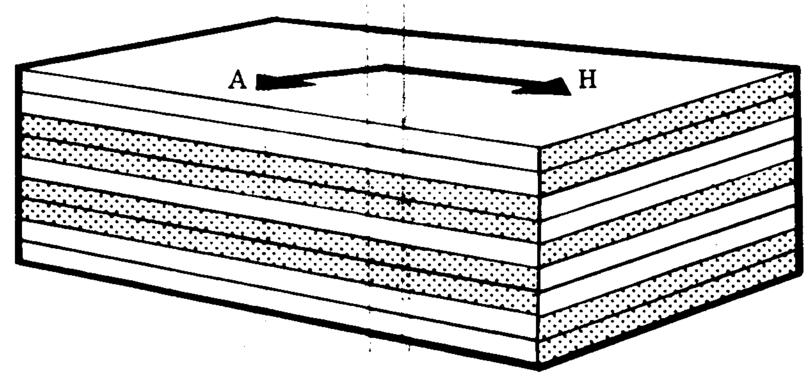


BIAXIAL ORIENTATION (2:1)

S-994 GLASS FILAMENT - 6 PLYS -
192 ENDS/IN./PLY
EPON 828/NMA/BDMA RESIN -
20 PERCENT BY WEIGHT

WOUND GLASS COMPOSITE

CONFIGURATION LOX - III

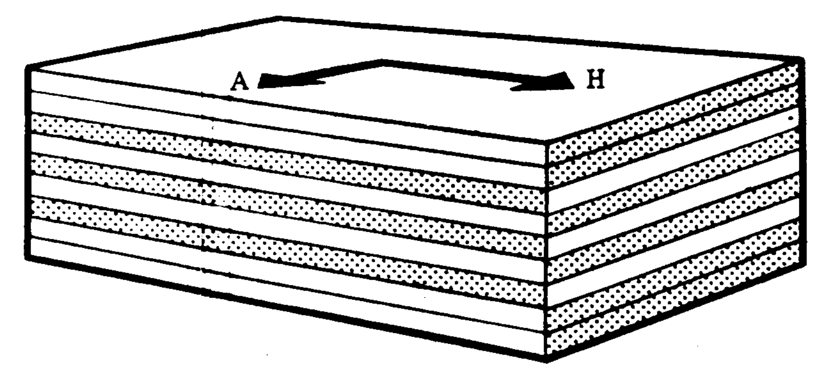


BIAXIAL ORIENTATION (2:1)

S-994 GLASS FILAMENT -
5 PLYS - 224 ENDS/IN./PLY
4 PLYS - 144 ENDS/IN./PLY
EPON 828/NMA/BDMA RESIN -
20 PERCENT BY WEIGHT

WOUND GLASS COMPOSITE

CONFIGURATION LH_2 - III



BIAXIAL ORIENTATION (2:1)

S-994 GLASS FILAMENT - 9 PLYS -
208 ENS/IN./PLY
EPON 828/NMA/BDMA RESIN -
20 PERCENT BY WEIGHT

FIGURE 8 SKEENING COMPOSITE
FACE SHEETS

SELECTION OF FACE MATERIALS

Monolithic Metals

In the PRELIMINARY WEIGHT COMPARISON it was found that sandwiches with faces of high strength titanium alloys and steels were potentially lighter than a sandwich with 2219-T87 faces, the standard of comparison. Based on this the following alloys were chosen for further more refined study in the screening composite phase.

Titanium Alloys

Ti-6Al-4V, HT(STA) and Ann

Ti-4Al-3Mo-1V (HT)

Ti-8Al-1Mo-1V

Steels

301 XFH

18Ni Maraging (250 Grade)

PH14-7Mo RH 1075

Other titanium and steel alloys could have been chosen for study. However, the above are representative of three of the most useful classes in each base material category, all are commercially available, and there is considerable experience in their fabrication and processing. Sandwiches with faces of these materials were all found to be lighter than the standard aluminum sandwich in a refined analysis, (see SCREENING COMPOSITE WEIGHTS, below). However, only the 6Al-4V and the Maraging and PH15-7Mo steels were procurable in the sizes and quantities and within the schedule required for the program, and hence only these were included in the twelve Screening Composites for fabrication and testing.

Composite Face Materials

Sheets of the following composite faces, chosen on the basis of their potentially high efficiencies as structural materials were fabricated and tested for their mechanical properties earlier in the program (refer to Fabrication and Testing of Composite Sheet).

Titanium alloy + steel wire

Aluminum alloy + steel wire

Glass fibers in resin plastic

Glass fibers and wire in plastic

Steel wire in plastic

Test results indicated that the aluminum + wire and the titanium + wire sheets were considerably more efficient in tension strength in the direction of the wires than them the standard of comparison, 2219-T87 aluminum alloy. Their compression properties across the wires and their elastic moduli, on the other hand, were lower than that of aluminum. The aluminum + wire material was chosen for further evaluation in the program and was eventually shown by analysis to be more efficient as a sandwich face than the aluminum alloy, (refer to SCREENING COMPOSITE WEIGHTS) and was included as one of the twelve Screening Composites. Aluminum alloy 2014-T6 was used in the laminate since there is experience with its use in SATURN construction. Thin adhesive films were used for bonding in order to reduce dead weight as suggested previously, (refer to Testing of Composite Sheet).

The titanium + wire composite sheet was not investigated further in the program due to limitations of budget and scheduling and the fact that the aluminum + wire would have a wider range of usefulness as a container material. Titanium is not used in contact with liquid oxygen because of the explosion hazard.

The S-994 glass fiber + resin composite sheets in tests showed both high tension and high compression strength in comparison to the aluminum standard. This material was also eventually shown by analysis to be more efficient in a sandwich than the aluminum standard and was included in the Screening Composites.

The glass-fiber materials used in the Screening Composites were fabricated by two methods, see Figure 8. The winding technique as described in Appendix C was used for some faces. Other glass-fiber faces were made from purchased "glass tapes". These "tapes" are thin (about 5 to 10 mils thick) sheets of 20-end unidirectional glass filament yarn, preimpregnated and held together by a resin matrix. In making a glass tape face sheet, a pre-determined number of the glass tapes are pressed together and cured into a single, laminated sheet. Other materials, for example wire, may be sandwiched between the glass tapes to make a composite face sheet. In comparison with wound glass filament sheet, glass tape sheet may be less costly and less difficult to fabricate. In addition, the properties of glass tape sheet may be more reproducible than those of wound glass filament sheet.

Steel wire in a resin matrix was not evaluated further for tension applications in the program because of its low tension efficiency compared to the glass fiber + resin material as shown in tests. However, test on a composite of glass fiber + wire indicated that such a material may show advantages when the glass is loaded in tension and the wire in compression. A composite sheet of this type was further analytically evaluated in the program and included in the Screening Composites.

Propellant Containment Considerations

The choice of the face sheet combinations for the configurations of Figure 7 was influenced by considerations of propellant compatibility and of temperature conditions due to the contained cryogenic liquids.

Titanium alloys are not proposed for direct contact with liquid oxygen in recognition of the potential explosive nature of this combination. The glass-fiber composite is proposed for contact with several liquids including liquid oxygen. This composite will require an internal barrier seal of some sort to prevent chemical action and/or permeation when used with any of the liquids. Work is in progress to develop sealing materials for glass fiber composites, Reference 41, and it is assumed, for the purpose of this program, that they will eventually become available.

The literature on cryogenic properties of materials furnishes only rough guidelines to the selection of materials for booster cryogenic tankage. However, there are some well marked differences in the reactions of materials to low temperatures as shown below by data from References 33 and 42:

Sharp Notch to Un-Notch

Tensile Ratio

Material	Ratio -320 F	Ratio -423 F
Aluminum 2014 T6	70	64
Titanium 6Al-4V, Ann	59	42
Titanium 6Al-4V, HT	39	32
PH15-7Mo, RH 1050	18	-
18Ni Maraging Steel, 280 Grade	55	30

These reactions were taken into account in the selection of the monolithic metal face sheets. The high strength steels were restricted to use with hydrocarbon fuels. Heat treated titanium was not used in contact with cryogenic liquids. However, titanium was proposed for the outer face of sandwiches where the inner face is in contact with a cryogenic liquid for example LH_2-II and LOX-I. In these cases it is assumed that the inherently low thermal conductance of the honeycomb sandwich will produce a sufficiently steep temperature gradient between faces to allow the use of a high strength material on the outer face.

Glass-fibers and steel wires are proposed for elements in composites for several cryogenic applications. It is believed that the discontinous nature of these materials may offset any embrittling effects by tending to limit crack propagation.

It will be noted that a number of configurations are suitable for use with several liquids, for example the aluminum + wire, LN_2-II, could be proposed for all liquids and the titanium configuration, LN_2-I, could be proposed also for LH_2 and hydrocarbon fuel.

SELECTION OF CORE MATERIALS

Following the preliminary weight comparisons, a decision was made to limit the investigation of composites to the study of sandwiches with honeycomb cores. The principal reasons for this limitation are: (1) The use of a single core configuration considerably simplifies the comparison between aluminum alloy faced honeycomb sandwich and sandwiches with faces of other high strength materials, and (2) optimization of core weight is avoided, a design effort which was considered outside the scope of the program.

Choice of the types of honeycomb core used in the screening composites of Figure 7 was determined by considerations of availability, weight, joining and thermal conductance. Aluminum honeycomb core 5052-H39, density 4.4 lb/cu ft, was used in all the screening configurations, except the LN_2-I and the LH_2-II. It was originally intended to use 3 lb/cu ft density metal cores in the Screening Composites. An earlier study (refer to Honeycomb Core Comparison) indicated that core of about 4.4 lb/cu ft minimum density would stabilize all face materials under a 6000 lb/in ultimate axial compression load. Since the screening composites were to be evaluated and tested under a lower axial load of 4000 lb/in (refer to Screening Composite Weights) it appeared that the minimum density requirement could be reduced to 3 lb/cu ft. Titanium honeycomb core, Ti-75A, 3 lb/cu ft, was procured and used in the titanium faced sandwich LN_2-I. Aluminum core, 3 lb/cu ft, was also used in the duplex core sandwich LH_2-II. It was found, however, that the 3 lb/cu ft cores were being damaged during machining and other handling of test specimens, and it was decided to change to the 4.4 lb/cu ft core in the remaining screening composite configurations in order to eliminate such effects.

The earlier core requirement study indicated that for a given core density, aluminum would provide more local support for the face sheet than steel, plastic, or glass fabric cores. Stocks of aluminum core also were more readily available than other honeycomb cores. Some consideration was given to the use of titanium core, solid state bonded to the titanium faces, for the LN_2-I configurations and to the use of a PH15-7Mo core brazed to the PH17-Mo faces in the HF-I configuration. The use of solid state diffusion bonding was attractive since it would eliminate the weight of the adhesive. However, in some preliminary experiments conducted under an NAA in-house program, Reference 43, attempts to diffusion bond 3 lb/cu ft titanium core to 0.040 in titanium sheet resulted in some core crushing and in incomplete face to core bonds. Since the schedule did not permit further investigation along this line, the titanium core was adhesive bonded to the faces in the LN_2-I configuration. The possibility of core crushing led to the decision to use adhesive bonding rather than brazing for face to core joining in the PH15-7Mo faced configuration HF-I. Considerable pressure is usually required to mate faces and cores in brazed honeycomb sandwich, and experience to date with PH17-Mo honeycomb sandwich brazing has been with cores of greater density, and, hence with greater crushing resistance, than the 4.4 lb/cu ft core.

A problem in SATURN liquid hydrogen tanks is minimizing the flow of heat from the outside environment through the tank walls. Currently, tank external insulation weighing about 0.3 lb/sq ft is used to reduce the heat flow to an acceptable level. This insulation is non-structural and therefore, is dead weight. As noted previously (refer to Honeycomb Core Comparison) use of a structural sandwich core of Mylar plastic or glass fabric may provide the necessary thermal barrier at a net weight saving. In the case of the " H_2" configurations, the potential for heat transfer between faces is reduced by special core design utilizing glass fabric core. A section of aluminum honeycomb next to the inner wall provides a sealed area in which a partial vacuum will be obtained by freezing of contained gases. Next to the outer face is a section of glass fabric honeycomb core sealed off from the aluminum core by an aluminum foil. The glass fabric is of 9 lb/cu ft density, which provides a shear modulus roughly equivalent to a 3 lb/cu ft aluminum, which is generally sufficient for tank column stabilization. The dense glass fabric core is restricted to narrow section in order to minimize core weight. The glass fabric was not used on the inner face since it is not sufficiently impermeable to gases to provide effective self evacuation by cryo-freezing. Mylar is impervious to gases and could be used effectively on the inner wall. At the present time, however, it is only available in densities up to about 3 lb/cu ft, which would not furnish sufficient support for the sandwich faces.

SCREENING COMPOSITE WEIGHTS

Requirements

The requirements and analytical formula used in establishing sandwich face thickness and core depths for weight comparisons of the Screening Composites are, in general, the same as those used in the preliminary weight comparison (refer to ANALYTICAL STUDIES) except that a 4000 lb/in axial ultimate load was used instead of 6000 lb/in. The lower axial load was adopted for the following reasons: (1) to reduce the core depth, which in some sandwich configurations was considerably out of proportion to other dimensions in the small size test coupons used in this program and (2) certain materials, notably the aluminum with unidirectional wires, appeared potentially more advantageous in applications where the ratio of hoop to axial load was fairly large (refer to PRELIMINARY WEIGHT COMPARISONS).

The concept of limit load was used in the screening composite weight analysis. Thus:

Ultimate Hoop Load (10.400 lb/in) = 1.4 X Limit Hoop Load (7400 lb/in)

Ultimate Axial Load (4000 lb/in)= 1.4 X Limit Axial Load (2860 lb/in).

General procedures for establishing limit stresses for the composite face materials are illustrated in Figures 9 and 10. Figure 9 represents a case in which the same material, in this case Titanium-6Al-4V alloy, is used for both face sheets of a sandwich composite. The limit stresses, $F_{tu}/1.4$, $F_{ty}/1.1$, and $F_{cy}/1.1$, which are the material allowables divided by the factors of safety, are located on the curve. If the hoop tension is critical, the limit stress $F_{tu}/1.4$, being smaller than $F_{ty}/1.1$, and the hoop limit load would be used to calculate face sheet thickness. If the axial compression load is critical, the limit stress, $F_{cy}/1.1$, and the axial limit load would establish face sheet thickness.

Figure 10 illustrates how limit stresses are established for sandwiches with unlike faces. For a tension critical structure, the lowest $F_{tu}/1.4$ or $F_{ty}/1.1$ for the two materials is located, in this case $F_{ty}/1.1$ for the aluminum. This is the limit stress for the aluminum. Since the two materials are strained together, the limit stress for the titanium is the stress in the titanium corresponding to the strain produced by a stress of $F_{ty}/1.1$ in the aluminum. In this case, the value of limit stress in the aluminum limits the allowable stress in the titanium to a value considerably below the normally used limit stresses ($F_{tu}/1.4$ and $F_{ty}/1.1$). The titanium is, therefore, not used to maximum efficiency in this composite.

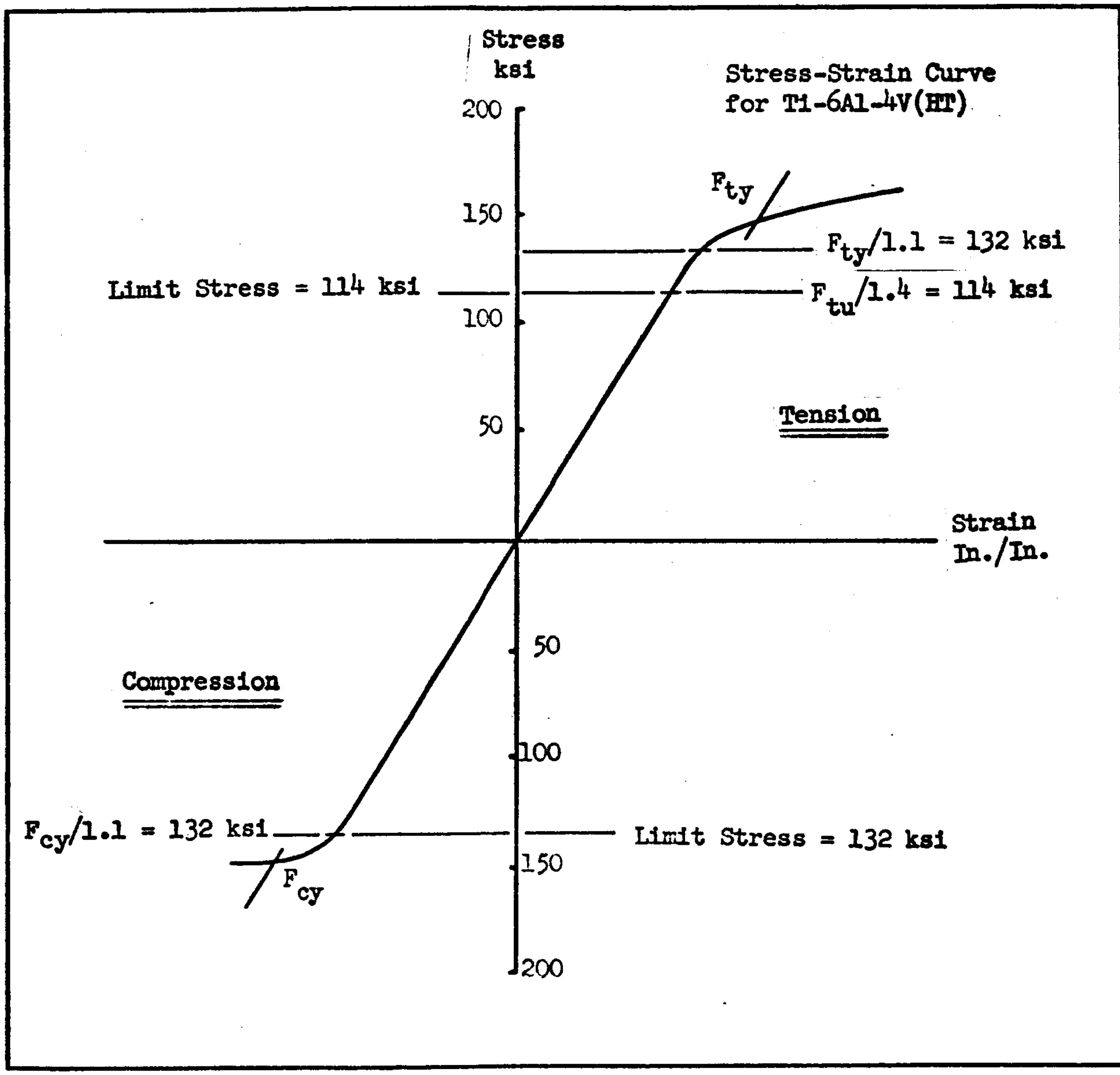


FIGURE 9 LIMIT STRESSES FOR SANDWICH WITH LIKE FACES

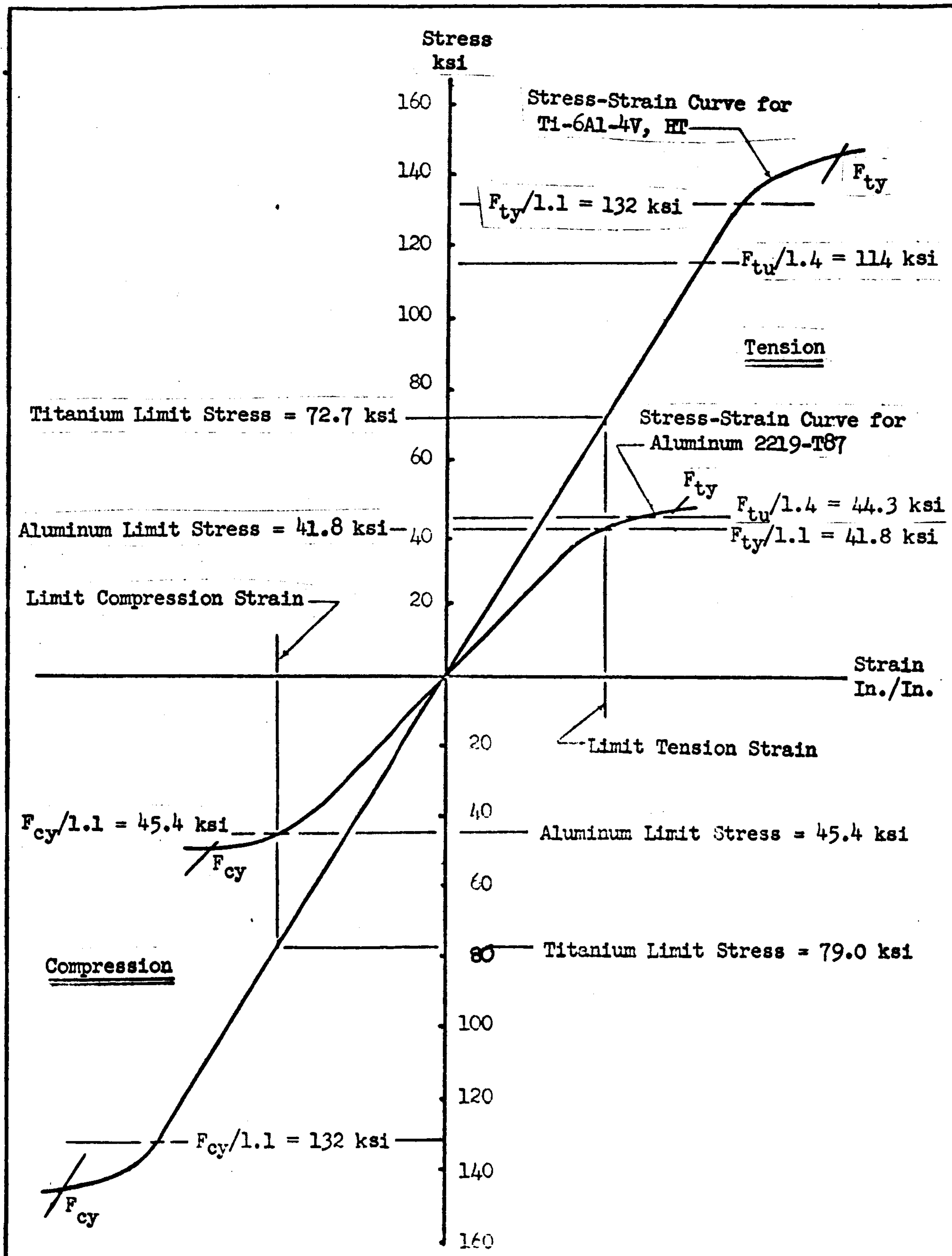


FIGURE 10 LIMIT STRESSES FOR SANDWICH WITH UNLIKE FACES

A brief analysis was conducted to establish the procedure for arriving at minimum weights for sandwich configurations with isotropic face sheet materials. These optimizations are operational within the criteria of this project only. The two principal variables establishing sandwich weight are core weight and face sheet weight. The analysis revealed the following:

1. Minimum weight in sandwiches with the same material in both faces is achieved by selecting face sheet thicknesses which will allow the faces to work at limit stresses. Although this procedure tends to maximize core depths, minimizing face sheet weight more than offsets added core weight, because of the low density of the cores.
2. For sandwiches with the same material in both face sheets, minimum weight is achieved when both faces are the same thickness.

Material Design Properties

Metallic facing material properties that were used for design of composite specimens for the screening tests are given in Table X. The source of these data is, generally, the NAA/LAD Material Properties Handbook.

The properties of the composite facing materials sheets used for design are listed in Table XI. The properties listed for the wound glass filament or glass tape composites are based on the tests conducted to date in this program on wound glass filament sheet (refer to Fabrication and Testing of Composite Sheet) and also, in the case of the glass tapes, on supplier data, Reference 39.

TABLE X

METALLIC FACING MATERIAL DESIGN PROPERTIES

Material	Density (lb/cu in.)	Tension Ultimate (ksi)	Tension Yield, 0.2% (ksi)	Compression Yield, 0.2% (ksi)	Modulus of Elasticity (10^6 psi)	Compression Modulus (10^6 psi)
Aluminum Alloy Sheet						
2219-T87	0.102	62	50	50	10.5	10.8
2014-T6	0.101	67	59	60	10.5	10.7
Titanium Alloy Sheet						
6Al-4V ANN	0.160	130	120	120	15.9	16.5
6Al-4V HT		160	145	145	16.3	16.3
8Al-1Mo-1V	0.158	135	125	135	17.5	18.0
4Al-3Mo-1V HT	0.163	170	150	150	16.4	16.4
Steel Sheet						
PH15-7Mo	0.277	200	180	190	29.0	30.0
301 XFH	0.286	200	160	L 120, T 189	27.5	28.3
Maraging (250 grade)	0.289	255	245	245	26.5	28.3
Steel Wire						
0.010 in. dia.	0.30	385	300	300	30	30
0.004 in. dia.	0.30	585	460	460	30	30
0.015 in. dia.	0.30	365	290	290	30	30

TABLE XI

COMPOSITE FACING MATERIAL DESIGN PROPERTIES

Composite (1)	Density (lb/cu in.) (2)	Tension Ultimate (ksi)	Tension Yield, 0.2% (ksi)	Compression Ultimate (ksi)	Modulus of Elasticity (10^6 psi)	Compression Modulus (10^6 psi)
Wound Glass Filament or Glass Tape "2" direction "1" direction	0.080	125 -	(3) -	- 35 (3)	5.5 -	- 4.0
Glass Tape-Wire With wire (axial) Across wire (hoop) (Estimated properties)	0.115	- 125	- (2)	60 (3) -	- 5.35	6.00 -
2014 Aluminum-Wire With wire (hoop) Across wire (axial) (Estimated properties)	0.131	146 -	110 -	0.2% Comp. Yield ksi - 40	12.7 -	- 6.7

(1) See Figure 10 for composite descriptions.
(2) Theoretical density based on nominal compositions.
(3) No yielding or less than 0.2% offset prior to ultimate failure.

The tension design properties of the 2014 aluminum + wire laminate were calculated by the use of the method of Appendix E and Equation (2) (refer to FABRICATION AND TESTING OF COMPOSITE SHEETS - Analysis of Test Results). The compression properties were calculated on the basis that the wire, oriented normal to the axial direction, does not carry any compression load. The design properties of glass tape-wire laminates were based on some previous NAA/LAD work on glass-wire laminates, Reference 44.

Configuration Details and Weights.

The details and weights of the twelve Screening Composite configurations plus the standard of comparison, 2219-T87 sandwich, are given in Table XII. All selected configurations have lower total weights than that of the standard aluminum sandwich. Total weights represent only the face sheets and cores. Adhesive bonding, protective finishing, and sealing weights are neglected. It should be noted that the aluminum sandwich should have some increment of insulation weight added for a valid comparison with the LH_2 configurations. A core density of 4.4 lb/cu ft was used for weight calculation although some configurations were actually fabricated with 3 lb/cu ft core (refer to CORE MATERIALS). Also shown in Table XII are some sandwich configurations studied which were lighter than the aluminum sandwich but which were not selected for screening composites for reasons discussed previously (refer to FACE MATERIALS).

FABRICATION OF SCREENING COMPOSITES

The twelve screening composites were fabricated according to the details shown in Figures 7 and 8 and Table XII. One 10 in. x 14 in. panel was fabricated for each of the composites with monolithic faces and for

TABLE XII
SCREENING COMPOSITES CONFIGURATION DETAILS

Screening Composite Designation	Face Material	Limit Load (lb/in.) Limit Stress (ksi)		Face Sheet Thickness (in.)	Face Sheet Weight (psf)	Core Depth (in.)	Core Weight (psf)	Total Weight (psf)
		Hoop	Axial					
Aluminum Honeycomb (Standard)	Alum 2219-T87 (Outside)	3700 41.8	1430 16.2	0.088	1.24	0.88	0.32	2.80
	Alum 2219-T87 (Inside)	3700 41.8	1430 16.2	0.088	1.24			
LN_2-I	TI 6Al-4V ANN (Outside)	3700 93.0	1430 36.0	0.040	0.92	1.22	0.45	2.29
	TI 6Al-4V ANN (Inside)	3700 93.0	1430 36.0	0.040	0.92			
LN_2-II	2014 Aluminum-Wire (Outside)	3700 82.3	1430 31.8	0.045	0.85	1.93	0.71	2.41
	2014 Aluminum-Wire (Inside)	3700 82.3	1430 31.8	0.045	0.85			
LN_2-III	Glass Tape-Wire (Outside)	3700 74.0	1430 28.6	0.050	0.87	2.33	0.86	2.60
	Glass Tape-Wire (Inside)	3700 74.0	1430 28.6	0.050	0.87			
LOX-I	TI 6Al-4V HT (Outside)	3410 114	1765 59.1	0.030	0.69	1.8	0.66	2.20
	2014 Aluminum-Wire (Inside)	3990 88.8	1095 24.3	0.045	0.85			

TABLE XII (CONTINUED)
SCREENING COMPOSITES CONFIGURATION DETAILS

Screening Composite Designation	Face Material	Limit Load (lb/in.) Limit Stress (ksi)		Face Sheet Thickness (in.)	Face Sheet Weight (psf)	Core Depth (in.)	Core Weight (psf)	Total Weight (psf)
		Hoop	Axial					
LOX-II (Glass Tape) and LOX-III (Wound Glass)	Glass (Outside)	3700 65	1430 25	0.057	0.61	3.0	1.10	2.32
	Glass (Inside)	3700 65	1430 25	0.057	0.61			
LH_2-I	Wound Glass (Outside)	1320 33	370 9.25	0.040	0.43	1.93	GL H/C .19 AL H/C .49 AL Foil .03 Total 0.71	2.65
	TI 6Al-4V ANN (Inside)	6080 93	2490 38.1	0.065	1.51			
LH_2-II	TI 6Al-4V HT (Outside)	3700 95.2	1430 36.8	0.039	0.90	GL H/C .25 AL H/C .99 Total 1.24	GL H/C .19 AL H/C .36 AL Foil .03 Total 0.58	2.40
	TI 6Al-4V ANN (Inside)	3700 93	1430 36	0.040	0.92			
LH_2-III	Wound Glass (Outside)	2900 45	1320 20.5	0.065	0.69	GL H/C 0.25 AL H/C 2.63 Total 2.88	GL H/C .19 AL H/C .97 Al Foil .03 Total 1.19	2.73
	2014 Aluminum-Wire (Inside)	4500 100	1540 34.2	0.045	0.85			
HF-I	PH15-7Mo Steel (Outside)	3700 143	1430 55.2	0.026	1.04	1.03	0.38	2.46
	PH15-7Mo Steel (Inside)	3700 143	1430 55.2	0.026	1.04			

TABLE XII (CONTINUED)

SCREENING COMPOSITES CONFIGURATION DETAILS

Screening Composite Designation	Face Material	Limit Load (lb/in.) Limit Stress (ksi)		Face Sheet Thickness (in.)	Face Sheet Weight (psf)	Core Depth (in.)	Core Weight (psf)	Total Weight (psf)
		Hoop	Axial					
HF-II	Maraging Steel (Outside)	5860 182	2433 75.5	0.032	1.34	2.1	0.77	2.54
	Wound Glass (Inside)	1540 38.5	427 10.7	0.040	0.43			
HF-III	TI 6Al-4V HT (Outside)	3700 114	1430 44.1	0.032	0.74	1.52	0.56	2.04
	TI 6Al-4V HT (Inside)	3700 114	1430 44.1	0.032	0.74			
	301 X FH Steel (Outside)	3700 143	1430 55.2	0.026	1.07	1.10	0.40	2.54
	301 X FH Steel (Inside)	3700 143	1430 55.2	0.026	1.07			
	TI-8Al-1Mo-1V (Outside)	3700 96.5	1430 37.4	0.038	0.87	1.19	0.44	2.18
	TI-8Al-1Mo-1V (Inside)	3700 96.5	1430 37.4	0.038	0.87			
	TI-4Al-3Mo-1V(HT) (Outside)	3700 121	1430 46.7	0.031	0.73	1.57	0.58	2.08
	TI-4Al-3Mo-1V(HT) (Inside)	3700 121	1430 46.7	0.031	0.73			

the glass-tape configuration LOX-II. Two 9 in x 9 in. panels were made for each of the configurations requiring winding of the face sheets. The methods used to fabricate the composite face materials and the panels are described in detail in Appendix C. As previously noted 4.4 lb/ft^{-2} 5052-H39 aluminum core was used with all configurations except the LN_2-I and the LN_2-II in which 3 lb/cu ft Ti-75A core and 3 lb/cu ft 5052 H39 core were used, respectively. FM-1000 adhesive was used at 0.06 lb/ft^{-2} for the core to face bonds and the core to aluminum foil bonds (LH_2 configurations). One of the screening panels marked off for test specimen removal is shown in Figure 11.

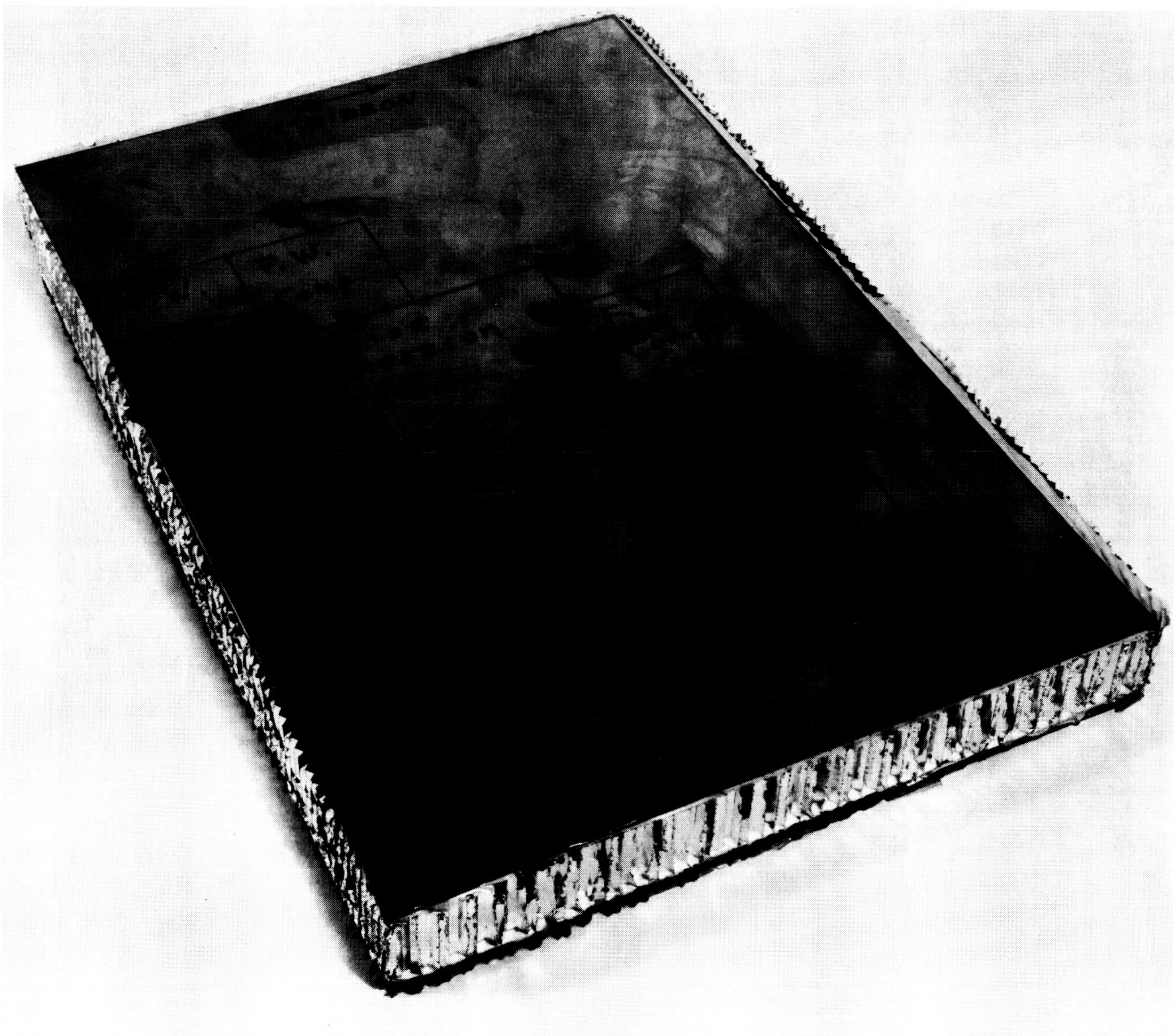
TESTING OF SCREENING COMPOSITES

The Phase I screening composite evaluation consisted of the following three types of tests:

1. Flatwise tension
2. Flatwise compression
3. Edgewise compression

The edgewise compression tests were conducted in the axial direction (Refer to Figure 8). The three types of specimens are shown in Appendix D. End stability of the edgewise compression specimens was obtained by potting an aluminum channel to the ends with resin.

The specimens were tested at room temperature in accordance with MIL-STD-401A. Strain was recorded along with load in the flatwise and edgewise compression tests. In several of the edgewise compression tests, the uniformity of the loading system was verified by use of a strain gage recording system simultaneously with the conventional extensometer system. The strain gages were mounted on each face sheet



Faces: Ti-6Al-4V
Core: Aluminum HC + Glass HC

FIGURE 11 SCREENING COMPOSITE PANEL LH_2-II and output correlated to the extensometer reading. Further details of the testing procedures are given in Appendix D.

FLATWISE COMPRESSION TEST RESULTS

Results of these tests on all Phase I composite configurations are presented in Table XIII. The lower ultimate values obtained in the LN_2-I and the LH_2-II configurations are due to the use of 3 lb/cu ft core. In the duplex core configurations, failure occurred in the aluminum core. The results on aluminum core compare with reported compression data. For example, Reference 45 gives for bare cores: 282 psi typical ultimate for 3 pcf 5052 H39 core and 489 psi typical ultimate for 4 pcf 5052 H39 core.

FLATWISE TENSION TEST RESULTS

Results of these tests on all Phase I composite configurations are presented in Table XIV. A great amount of scatter was obtained in the reported values. Failures occurred predominately in the bonds between core and adhesive or the face and adhesive rather than in the core. Adhesion was particularly low to titanium faces, for example, in the LN_2-I and HF-III configurations. Typical core to adhesive and face to adhesive failures are shown in Figure 12. The generally unsatisfactory results are attributable principally to poor cleaning procedures. Vapor degreasing was used for core cleaning. This process is generally satisfactory for dense cores. However, with the lightweight cores used, the core foil reaches the vapor temperature very quickly and condensation of the vapor, and consequently the cleaning action, then ceases. Failure to refrigerate the adhesive used (FM-1000), which is subject to deterioration at room temperature, may have been a contributing factor. As a

TABLE XIII

SCREENING COMPOSITES

FLATWISE COMPRESSION TESTS

Composite Configuration	Ultimate Stress (psi)	Modulus (psi)	Composite Configuration	Ultimate Stress (psi)	Modulus (10^6 psi)
LN_2-I (2)	162 279 253	0.0193 0.0421 0.0430	LH_2-I	451 341	0.151 0.0929
LN_2-II	389 423 434	0.121 0.184 0.141	LH_2-II (2)	277 273	0.199 0.210
LN_2-III	367 416 357	(1) (1) 0.165	LH_2-III	523 458 487	0.175 0.155 0.177
LOX-I	433 413 488	0.171 0.227 0.262	HF-I	581 551 570	0.187 0.185 0.187
LOX-II	571 524 524	0.223 0.260 (1)	HF-II	475 472 559	0.249 0.175 0.206
LOX-III	384 484 451	0.159 0.213 0.249	HF-III	522 585 538	0.209 0.217 0.165

(1) Results not available due to extensometer malfunction.
(2) 3 lb/cu ft 5052 H 39 Core. All other 4.4 lb/cu ft 5052 H 39 core.

TABLE XIV

SCREENING COMPOSITES

FLATWISE TENSION TESTS

Composite Configuration	Ultimate Stress (psi)	Failure Mode
LN_2-I	55.8	100% core-to-adhesive bond failure
	37.7	100% core-to-adhesive bond failure
LN_2-II	179	80% core-to-adhesive bond failure, 20% face sheet-to-adhesive bond failure
	124	100% face sheet-to-adhesive bond failure
	183	100% core-to-adhesive bond failure
LN_2-III	183	100% core-to-adhesive bond failure
	127	100% core-to-adhesive bond failure
LOX-I	99.0	90% titanium face sheet-to-adhesive bond failure, 10% core-to-adhesive bond failure with observed core crushing
	218	80% titanium face sheet-to-adhesive bond failure, 20% core-to-adhesive bond failure
LOX-II	439	100% core-to-adhesive bond failure
	413	100% core-to-adhesive bond failure
LOX-III	847	100% core failure
	812	90% core failure, 10% core-to-adhesive bond failure
	826	95% core failure, 5% core-to-adhesive bond failure
LH_2-I	51.2	70% aluminum core-to-adhesive bond failure, 30% titanium face sheet-to-adhesive bond failure
	261	2% glass core failure and glass face sheet delamination, 98% glass core-to-adhesive bond failure
	207	100% titanium face sheet-to-adhesive bond failure
LH_2-II	401	98% core failure, 2% bond failure (core crushing noted prior to testing)
	325	50% core failure, 50% bond failure (core crushing noted prior to testing)
LH_2-III	214	100% glass core-to-adhesive bond failure
	259	95% glass face sheet delamination, 5% glass core-to-adhesive bond failure
	157	Glass core-to-adhesive bond failure on aluminum foil side, aluminum core-to-aluminum foil adhesive bond failure

(Continued next page)

TABLE XIV (Cont'd)

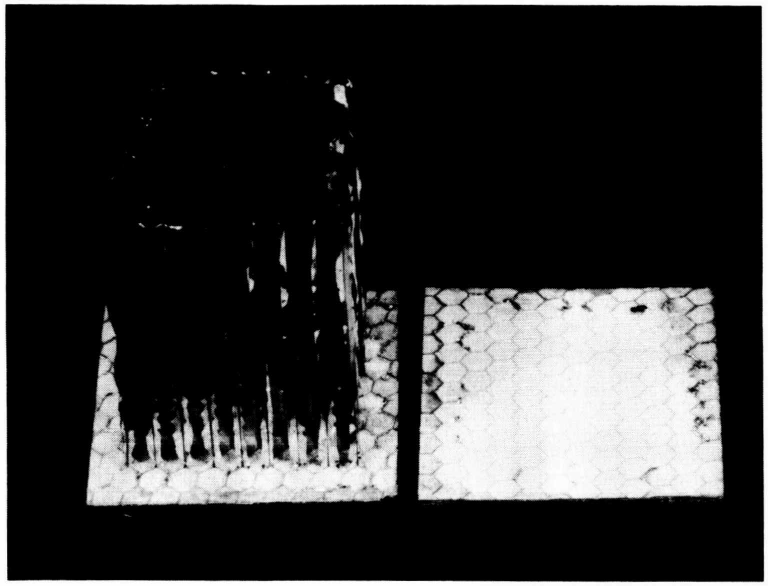
SCREENING COMPOSITES

FLATWISE TENSION TESTS

Composite Configuration	Ultimate Stress (psi)	Failure Mode
HF-I	482	100% core-to-adhesive bond failure
	409	100% core-to-adhesive bond failure
HF-II	468	75% aluminum core-to-adhesive bond failure, 25% steel face sheet-to-adhesive bond failure
	589	75% aluminum core-to-adhesive bond failure, 25% steel face sheet-to-adhesive bond failure
HF-III	81	100% face sheet-to-adhesive bond failure
	89	100% face sheet-to-adhesive bond failure
	113	100% face sheet-to-adhesive bond failure

Configuration LN_2-II
Faces: Aluminum + Wire
Core: Aluminum HC
Adhesive: FM-1000

183 psi



124 psi

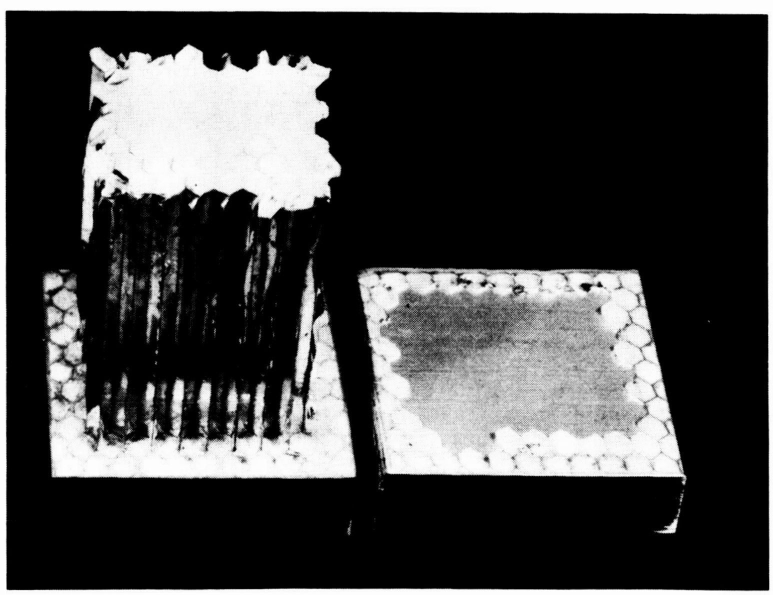


FIGURE 12 FLATWISE TENSION SPECIMENS

result of these tests a small test program to improve the adhesive bonding of core and metal facing sheets was conducted, (Refer to EVALUATION OF ADHESIVE BONDING TECHNIQUES).

EDGEWISE COMPRESSION TEST RESULTS

Results of these tests on the screening composite configurations are presented in Table XV. Also shown in this table are the stresses in the face sheets corresponding to the design ultimate axial compressive load of 4000 lb/in. These design values are obtained by multiplying the limit axial stresses given in Table XII by the safety factor of 1.4.

It will be noted that the test values are much greater than the design values for many of the configurations. In these configurations the face sheet thicknesses were established by the 10,400 lb/in hoop ultimate load and, consequently, have a considerable margin of strength under the smaller axial load. Low and scattered compression test values were obtained in the LN_2-I and HF-III configurations. These results are attributable to the low strength bond between the adhesive and the titanium faces (refer to Flatwise Tension Test Results).

Lower compression test values in relation to the design values, were obtained for the LN_2-II, LN_2-III, LOX-II, and LH_2-III configurations. In all of these configurations face sheet thicknesses were established by the compressive properties of the materials and, therefore, only relatively small margins of strength could be expected. In some cases test values fall below design values. In the case of the LN_2-III and LOX-II configurations the largely delaminating character of the failure mode may be responsible for the low test values. It should be noted that for the wound glass LOX-III configuration, which is sized by the compression

TABLE XV

SCREENING COMPOSITES
EDGEWISE COMPRESSION TESTS

Composite Configuration	Ultimate Stress (ksi) Test	Ultimate Stress (ksi) Design	Modulus (10^6 psi)	Failure Mode
LN_2-I	57.4	50.4	19.1	Core-to-adhesive bond failure on one face sheet
	80.3		19.1	Core-to-adhesive bond failure on both face sheets, both face sheets buckled
	78.5		17.9	Core-to-adhesive bond failure on both face sheets
LN_2-II	42.5	44.6	7.75	Face sheet wrinkling, core crushing and shear
	42.7		7.90	Face sheet wrinkling, core crushing and shear
	47.6		8.37	Face sheet wrinkling, core crushing and shear
LN_2-III	38.3	40.0	7.73	Face sheet delamination, core-to-facing bond failure
	31.6		7.58	Face sheet delamination, core-to-facing bond failure
	42.5		7.38	Face sheet delamination, core-to-facing bond failure
LOX-I (1)				
Al-Wire Face	53.7	34.0	5.86	Titanium face sheet-to-adhesive bond failure, core and bond failure at titanium face sheet, titanium face sheet buckled
Ti Face	137.3	83.0	15.0	
Al-Wire Face	51.2		7.18	Titanium face sheet-to-adhesive bond failure, core and bond failure at titanium face sheet, titanium face sheet buckled, aluminum-wire face sheet wrinkled, core crushing and shear
Ti Face	130.9		18.4	
Al-Wire Face	51.2		7.39	Titanium face sheet-to-adhesive bond failure, core and bond failure at titanium face sheet, titanium face sheet buckled, aluminum-wire face sheet wrinkled, core crushing and shear
Ti Face	130.9		18.9	
LOX-II	45.7	35.0	4.83	Face sheet shear and delamination with core crushing
	47.4		5.25	Face sheet shear and delamination with core crushing
	35.8		4.81	Face sheet shear and delamination with core crushing
LOX-III	67.9	35.0	4.91	Facing shear and delamination
	54.5		5.39	Facing shear and delamination, core crushing and shear

(Continued next page)

TABLE XV (Cont'd)

SCREENING COMPOSITES
EDGEWISE COMPRESSION TESTS

Composite Configuration	Ultimate Stress (ksi)		Modulus (10^6 psi)	Failure Mode
	Test	Design		
LH_2-I(1)				
Glass Face	49.5	12.9	5.99	Titanium face sheet-to-adhesive bond failure, core and bond failure at titanium face sheet, titanium face sheet buckling
Ti Face	127.9	53.0	15.5	
Glass Face	43.5		5.41	Titanium face sheet-to-adhesive bond failure, core and bond failure at titanium face sheet, titanium face sheet buckling, glass face sheet delamination and shear, aluminum and glass honeycomb core shear
Ti Face	112.4		14.0	
Glass Face	53.4		6.01	Titanium face sheet-to-adhesive bond failure, core and bond failure at titanium face sheet, titanium face sheet buckling, glass face sheet delamination and shear, aluminum and glass honeycomb core shear
Ti Face	135.6		15.3	
LH_2-II	60.3	51.0	17.5	Bond failure
	92.1	(2)	19.1	50% bond failure, 50% core failure
LH_2-III (1)				
Glass Face	29.4	28.7	4.89	Core-to-adhesive bond failure on aluminum-wire side, aluminum-wire face sheet wrinkled, bond failure on aluminum-wire face sheet
Al-Wire Face	41.8	48.0	6.97	
Glass Face	28.6		4.69	Glass face sheet delamination and shear
Al-Wire Face	40.7		6.68	
Glass Face	30.2		4.95	Core-to-adhesive bond failure on aluminum-wire side, aluminum-wire face sheet wrinkled, bond failure on aluminum-wire face sheet
Al-Wire Face	42.9		7.05	
HF-I	185.9	77.3	27.6	Core crushing and shear, core failure, face sheets buckled
	184.1		27.4	Core crushing and shear, core failure, face sheets buckled

TABLE XV (Cont'd)

SCREENING COMPOSITES
EDGEWISE COMPRESSION TESTS

Composite Configuration	Ultimate Stress (ksi) Test	Ultimate Stress (ksi) Design	Modulus (10^6 psi)	Failure Mode
HF-II (1)				
Glass Face	26.9	15.0	3.18	Glass face sheet delamination and shear, core crushing and shear, steel face sheet buckled
Steel Face	188.5	106.0	22.3	
Glass Face	26.2		4.15	Core-to-adhesive bond failure, core and bond failure at steel face sheet, steel face sheet buckled, glass face sheet delaminati on
Steel Face	183.4		27.7	
Glass Face	26.8		4.06	Core-to-adhesive bond failure, core and bond failure at steel face sheet, steel face sheet buckled
Steel Face	189.6		28.7	
HF-III	41.9	62.0	17.1	Bond failure on core crushed side
	155.3		15.2	Face sheet wrinkling and core crushing on one side, bond failure on other side
	93.8		16.8	Bond failure

NOTE: Tested in direction corresponding to axial orientation.

(1) For configurations with dissimilar faces:

1. Load was applied at the elastic center so that the faces would deflect equally.
2. Where failures in both faces are indicated, it was not possible to determine which face sheet failed initially.

(2) Average of slightly differing values for Ti HT and Ti ANN faces.

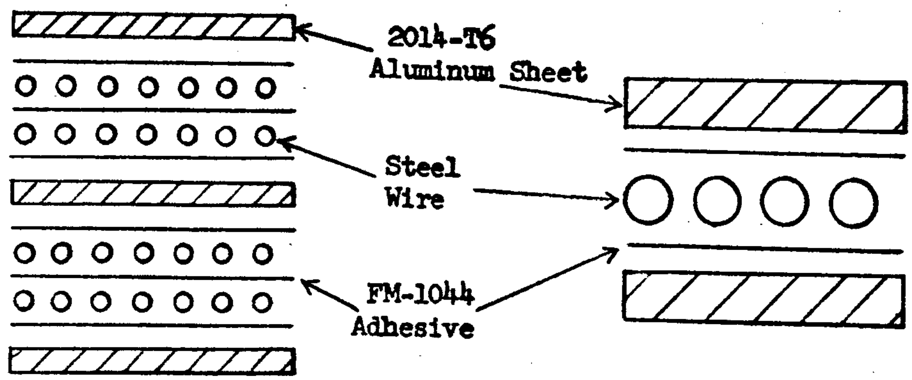
properties, the test values are higher in relation to the design values than in the case of the glass tape LOX-II configuration. This difference may be due to greater experience in fabricating the glass-fiber faces by the winding technique. In the case of the LN_2-II and LH_2-III configurations the low values may have been partly due to the erratic adhesive strength, both in the core to face bonds and in the aluminum to wire bonds.

The 4.4 lb/core honeycomb core configuration is apparently more than adequate for local stabilization of the faces as evidenced by the large margins by which the design stresses were exceeded in many cases. Where low test values were obtained,the causes were inadequate core to face adhesion or small margin of safety in the face material.

TESTING OF COMPOSITE SHEET

Tension tests were conducted on unidirectional glass-tape sheet and on aluminum + wire sheet to verify the design properties assigned to these materials (Refer to Table XI).

The glass sheet was prepared from Stratoglass 300 ST preimpregnated tape with 22% resin content by weight. Asbestos tabs were bonded to the ends of the glass specimens to provide additional gripping area and thus minimize stress concentrations. Two aluminum+wire composite configurations were tested. These are shown schematically in Figure 13. Test coupons of Configuration 1 were taken from the same composite sheet that was used for the faces of the LN_2-II screening composite configuration. A specially designed test specimen, shown in Figure 14, was employed for testing the aluminum-wire sheet. In this type of specimen, only the aluminum tabs and spacers are subjected to side loading by the testing grips and loads are transmitted to the aluminum-wire test coupon only by shear across the



Configuration 1		Configuration 2
0.010 in., 3 sheets	Aluminum	0.020 in., 2 sheets
0.004 in. dia., 4 plys, 192 wires/in./ply	Wire	0.015 in. dia, 1 ply, 56 wires/in./ply
6 layers, 0.001 in./layer	Adhesive	2 layers,0.003 in./layer

Figure 13. ALUMINUM+WIRE SHEET CONFIGURATIONS

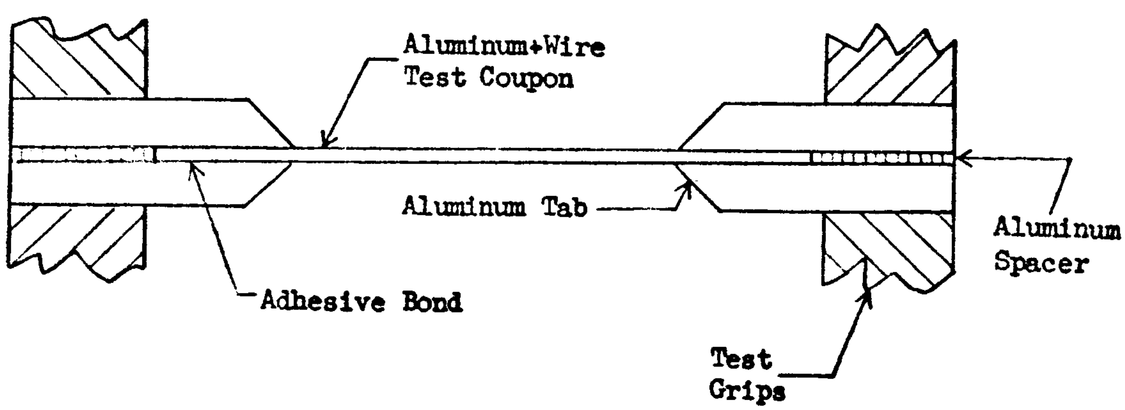


Figure 14. ALUMINUM+WIRE TEST SPECIMEN DESIGN

aluminum-wire/tab interface.

Results of the tests on the composite facing sheets are given in Table XVI. The lowest value obtained in a test section failure in the sheets of unidirectional glass tape lay-up was 185.5 ksi, which indicated a potential 120 ksi, or greater, strength in the "2" direction in a face sheet of this material with fibers at right angles in a 2:1 ratio. This value compares fairly closely with the 125 ksi design strength assigned to this type of material, as shown in Table XI. The glass tapes tested were the kind used in the LOX-II and LN_2-III screening composite configuration.

Premature failure occurred at a very low value in the aluminum + wire Configuration No. 1 sheet specimens. This type of sheet was used in the LN_2-II, the LOX-I, and the LH_2-III screening composite configurations. The failures, initiated near the reinforcing tab and may have been caused by a poor adhesive bond between the wire and aluminum and/or a notching effect near the tab. The failures in both configurations are shown in the section FAILURE ANALYSIS.

The aluminum + wire Configuration No. 2 Sheet does not represent any facing used in the screening composite configurations but was evaluated to demonstrate the feasibility of using a larger size wire in a laminate of this type. Such a laminate would be significantly less expensive to fabricate than the aluminum + wire Configuration No. 1 Sheet. The test results on the aluminum + wire No. 2 sheet verify the methods used to predict the properties of this type of composite. Figure 15 shows the close agreement obtained between the calculated and test values for both stress-strain and strength characteristics in this composite material.

TABLE XVI

COMPOSITE SHEET TENSION TESTS

Panel Designation	Specimen Thickness (in.)	Tension Strength (ksi)		Modulus of Elasticity (10^6 psi)	Failure Mode
		Ultimate	0.2% Yield		
Glass Tape (Unidirectional) (1)	0.028	124.0		7.70	Tab material failure
	0.028	185.5		7.10	Sequential fiber failure in test section
	0.029	230.3		8.23	Sequential fiber failure in test section
Aluminum-Wire Configuration 1 (2)	0.046	91.0	Less than 0.2% offset observed prior to failure	14.0	Failure of aluminum outside ply; aluminum-to-wire bond failure
	0.045	85.1		13.2	Failure of aluminum outside ply; aluminum-to-wire bond failure
Aluminum-Wire Configuration 2 (2)	0.060	105.7		11.4	Failure in test area
	0.060	100.0	85.0	13.1	Failure in test area

NOTE: Tests conducted in direction of glass or wire

(1) Stratoglass 300 ST preimpregnated glass tape, 8 plys, 130 ends/in./ply, 22% resins by weight.
(2) See figure 13 for configuration details.

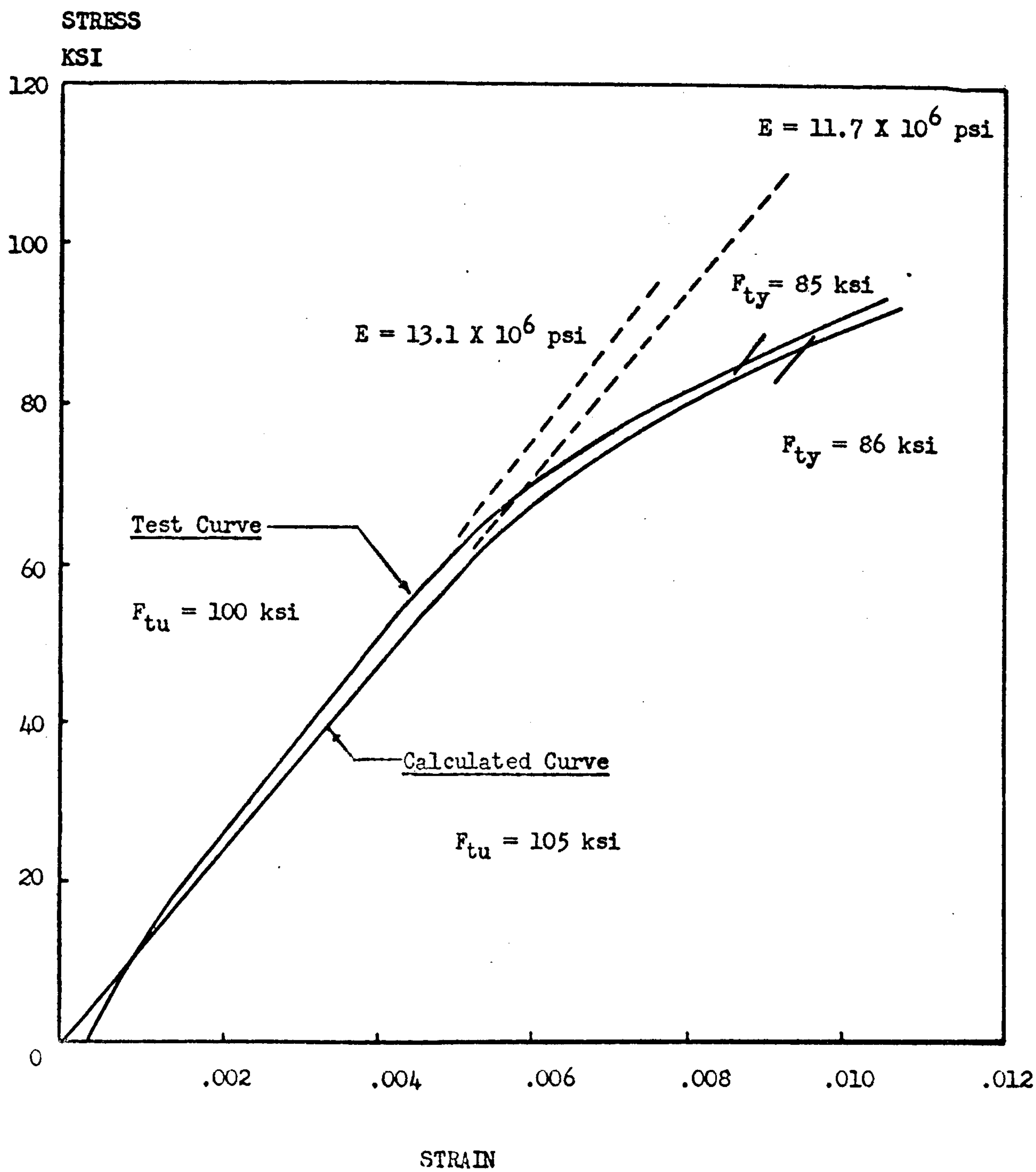


FIGURE 15 ALUMINUM + WIRE

TEST VS. CALCULATED PROPERTIES

EXPERIMENTAL PHASE II

OPTIMUM COMPOSITES

SELECTION OF OPTIMUM COMPOSITES

The following four composite configurations were recommended to, and approved by NASA/MSFC, for evaluation as optimum composites in Phase II.

OPTIMUM COMPOSITE NO.	PROPELLANT	PHASE I DESIGNATION
1	LN_2	LN_2-I
2	LOX	LOX-III
3	LH_2	LOX-I. Modified with a duplex core (see text)
4	HF	HF-1

Details of these configurations are shown in Table XVII. Facing sheet materials in these configurations have the same compositions and properties as those used in the corresponding Phase I composites (see Tables X and XI) except for the aluminum + wire laminate face. The aluminum + wire laminate in Optimum Composite No. 2 is similar to the No. 2 aluminum + wire laminate shown in Figure 13, but with thinner aluminum sheets. The calculated properties for this face material are given in Table XVIII.

TABLE XVIII

ALUMINUM+WIRE FACING

OPTIMUM COMPOSITE NO. 3

DIRECTION (1)	DENSITY (lb/cu in)	TENSION ULTIMATE (KSI)	TENSION YIELD (KSI)	COMPRESSION YIELD (KSI)	TENSION MODULUS (10^6PSI)	COMPRESSION MODULUS (10^6PSI)
W	0.133	124	98	—	12.7	—
A	—	—	—	40	—	6.7

(1) With wire direction (hoop) or Across wire direction (axial)

TABLE XVII

PHASE II OPTIMUM COMPOSITES

Config. No. (Fuel)	Face Sheets		Core	
	Description	Thickness (in.)	Description	Thickness (in.)
1 (LN)	Ti-6Al-4V, Cond A	0.040	Ti-75A H/C, 4.4 pcf	1.00
2 (LOX)	(1) Wound Glass (2:1): S-994 Glass Filament 5 plys, 224 ends/in./ply 4 plys, 144 ends/in./ply EPON 828/NMA/BDMA, 20 w/o	0.057	5052-H39 Aluminum H/C, 4.4 pcf	3.00
3 (LH)	Ti-6Al-4V, Cond STA (Outside)	0.030	Duplex Core: 0.25 in. HRP Glass H/C, 8 pcf (next to Alum-Wire face) 0.003 in. 3003 Aluminum Foil 1.55 in. 5052-H39 Aluminum H/C, 4.4 pcf	1.80
	Aluminum-Wire Composite: (Inside) 0.015 in. 2014-T6, 2 sheets 0.015 in. Steel Wire, 1 ply, 56 wires/in. FM-1044, 2 layers, 0.003 in./layer	0.045		
4 (HF)	PH15-7Mo, Cond RH 1075	0.026	5052-H39 Aluminum H/C, 4.4 pcf	1.03

0.09 psf and 0.06 psf FM-1000 used for face to core and core to foil bonds respectively in configurations No. 3 and No. 4.
0.135 psf HT-424 used for face to core bonds in configurations No. 1 and No. 2. Refer to text.
(1) Refer to Figure 10, LOX-III for make-up of glass sheet.

The compression yield for the aluminum + wire laminate of Table XVIII is the same as that of the aluminum + wire laminate used in the LOX-I screening composite (compare with Table XI). Since it is desired to keep the aluminum + wire compression yield margin of safety the same in Optimum Composite No. 3 as in the LOX-I screening composite, the thickness requirement for the aluminum + wire is the same for both composites (.045 in.).

Selection of the four optimum composites was based principally on weight comparisons, compatibility with the propellants, and thermal conductance. A comparison of the design weights of the Phase I Screening Composite configurations and the "Standard" composite (aluminum honeycomb sandwich) is presented in Table XIX. Except where noted, a simple 4.4-pcf core is assumed in calculating core weight. The duplex cores, combining insulative properties and structural strength, are composed of 4.4-pcf aluminum core, 9-pcf fiberglass core, and a 4-mil aluminum foil separator. A "Standard" composite with a duplex core is given for comparison with the other duplex core configurations. A LOX-I configuration modified with a duplex core is included, since this is felt to be a configuration of considerable potential utility. Adhesive weights are based on 0.09 pcf for each face sheet-to-core bond, and 0.06 pcf for each core-to-aluminum foil bond. The liner weight for sealing of inner fiberglass surfaces represents an adhesive bonded 2-mil aluminum foil, quilted to allow for differential strain, in the LOX and LN_2 configurations, and a bonded neoprene liner in the HF configurations. The percentage weight reductions are given by:

$$1 - \frac{\text{Screening Composite (simple core)}}{\text{Standard Composite (simple core)}} \times 100$$

and

$$1 - \frac{\text{Screening Composite (duplex core)}}{\text{Standard Composite (duplex core)}} \times 100$$

TABLE XIX
SCREENING COMPOSITES CONFIGURATION WEIGHTS

Screening Composite Designation	Outside Face / Inside Face	Face Weight (psf)	Core Depth (in.)	Core Weight (psf)	Adhesive Weight (psf)	Liner Weight (psf)	Total Weight (psf)	Weight Reduction (%)
STANDARD	Alum 2219-T37 / Alum 2219-T87	2.48	0.88	0.32	0.18	-	2.98	-
STANDARD Duplex Core	Alum 2219-T87 / Alum 2219-T87	2.48	Glass 0.25 Alum 0.63 0.88	Glass 0.19 Foil 0.03 Alum 0.23 0.45	0.30	-	3.23	-
LN_2-I (1)	Ti-6Al-4V ANN / Ti-6Al-4V ANN	1.85	1.22	0.45	0.18	-	2.48	17
LN_2-II	2014 Alum-Wire / 2014 Alum-Wire	1.70	1.93	0.71	0.18	-	2.59	13
LN_2-III	Glass Tape-Wire / Glass Tape-Wire	1.74	2.33	0.86	0.18	0.05	2.83	5.0
LOX-I	Ti-6Al-4V HT / 2014 Alum-Wire	1.54	1.80	0.66	0.18	-	2.38	20
LOX-I (1) Duplex Core	Ti-6Al-4V HT / 2014 Alum-Wire	1.54	Glass 0.25 Alum 1.55 1.80	Glass 0.19 Foil 0.03 Alum 0.57 0.79	0.30	-	2.63	19

(Continued next page)

TABLE XIX (Continued)
SCREENING COMPOSITES CONFIGURATION WEIGHTS

Screening Composite Designation	Outside Face / Inside Face	Face Weight (psf)	Core Depth (in.)	Core Weight (psf)	Adhesive Weight (psf)	Liner Weight (psf)	Total Weight (psf)	Weight Reduction (%)
LOX-II	Glass Tape / Glass Tape	1.30	3.00	1.10	0.18	0.05	2.63	10
LOX-III (1)	Wound Glass / Wound Glass	1.30	3.00	1.10	0.18	0.05	2.63	10
LH_2-I	Wound Glass / Ti-6Al-4V ANN	1.97	Glass 0.25 Alum 1.68 1.93	Glass 0.19 Foil 0.03 Alum 0.49 0.71	0.30	-	2.98	7.7
LH_2-II	Ti-6Al-4V HT / Ti-6Al-4V ANN	1.82	Glass 0.25 Alum 0.99 1.24	Glass 0.19 Foil 0.03 Alum 0.36 0.58	0.30	-	2.70	16
LH_2-III	Wound Glass / 2014 Alum-Wire	1.59	Glass 0.25 Alum 2.63 2.88	Glass 0.19 Foil 0.03 Alum 0.97 1.19	0.30	-	3.08	4.6
HF-I (1)	PH15-7Mo Steel / PH15-7Mo Steel	2.08	1.03	0.38	0.18	-	2.64	11
HF-II	Maraging Steel / Wound Glass	1.80	2.10	0.77	0.18	0.05	2.80	6.0
HF-III	Ti-6Al-4V HT / Ti-6Al-4V HT	1.48	1.52	0.56	0.18	-	2.22	25

(1)Selected optimum configurations for Phase II evaluation.

The LN_2-I and LOX-I configurations were chosen as Optimum Composites since they are attractive from both standpoints of weight saving and general utility. The LN_2-I configuration could be used with liquid nitrogen, liquid hydrogen, and hydrocarbon fuels. The LOX-I configurations has been modified by a change to a duplex core. This core will have the fiberglass honeycomb section next to the inner aluminum-wire laminate sheet. In the screening composites this duplex core was constructed with the glass-fabric next to the outer wall, since this core material is not impermeable to fluids (refer to <u>SELECTION OF SCREENING COMPOSITE CONFIGURATIONS</u>). Upon reconsideration however, it was decided to assume that glass-fabric core could be coated to render it impermeable or that mylar core of sufficiently high density would eventually become available for use. The LOX-I configuration, thus modified, would be suitable for use with all four propellant fluids.

The LOX-I, modified with the duplex core (Optimum Composite No. 3) is of considerable theoretical as well as practical interest, since it illustrates an efficiency advantage gained from both the use of double faced sandwich construction with a low density core and the use of composite material faces. The outer face of heat-treated titanium alloy is highly efficient but would not normally be considered for use in contact with liquid oxygen or at cryogenic temperatures. However, in this construction the titanium is isolated from deleterious propellant fluid and low temperature effects by the core and the aluminum inner face. The inclusion of high strength wires in the aluminum inner face allows this face to be designed for a high enough stress in the hoop direction to permit effective utilization of the high strength of the outer titanium face, refer to the limit hoop stresses for the LOX-I configuration in Table XII. Use of monolithic aluminum alloy, with its relatively low tension strength, for the inner face would restrict the allowable tension stress in the titanium to a relatively low value and necessitate an increase in the titanium sheet thickness (refer to the discussion of limit stresses in unlike faces under SCREENING COMPOSITE WEIGHTS - Requirements).

The LOX-III configuration provides a substantial weight saving under the loading conditions established for this program. Furthermore, as previously noted (refer to AXIAL LOAD EFFECTS) the advantage of such a configuration over aluminum sandwich would increase as the design axial compressive load decreases. This results from a greater incremental reduction in core depth in the glass sandwich as compared to the aluminum sandwich with a decreasing axial compressive load. In addition, evaluation of the LOX-III composite would establish a scientific first, since no prior data have been generated on the properties of thin sheets of glass fiber composites under compressive loading. Such information will form a foundation for further investigations of composites of this type with the improved filaments that are currently under development, for example, high modulus glass fibers and boron filaments.

The HF-I configuration offers a substantial weight saving. Also, its evaluation would furnish data on a potentially useful material of a distinctly different type from the others recommended.

Other Screening Composite configurations which offer substantial weight reductions are LN_2-II, LOX-II, LH_2-II, and HF-III. However, all the various face sheets and cores of these configurations are represented in the four optimum configurations recommended for Phase II testing. Also, the HF-III configuration may have limited potential utility because of the relatively low ductility of heat-treated titanium at cryogenic temperatures. The LOX-III configurations was chosen over the LOX-II primarily because of the greater amount of experience in fabricating faces from wound glass than from glass tape.

FABRICATION OF OPTIMUM COMPOSITES

GENERAL PROCEDURES

Fabrication of the face sheets and the assembling of sandwich elements of the optimum composites were accomplished, generally, in the same manner as the corresponding screening composite configurations. Fabricating and processing details are given in Appendix C.

SELECTION OF ADHESIVE

The FM-1000 adhesive was selected originally over HT-424 adhesive for use with all the optimum composites. This choice was based on existing lap shear data on the materials from References 46 to 49, Figure 16, which indicated that the FM-1000 was competitive over the temperature range and on its lower density as compared to HT-424. However, tests results on Configuration Nos. 3 and 4 showed the FM-1000 core to face bonds to be unexpectedly weak at 212°F (refer to OPTIMUM COMPOSITE TEST RESULTS). As a result of this difficulty with FM-1000 a change was made to HT-424 in Configuration Nos. 1 and 2. It should be noted that substitution of the HT-424 in the same thickness as the FM-1000 results in a slightly higher weight for these configurations and, hence, their percent weight advantage over the 2219-T-87 sandwich, also joined with the HT-424, would be slightly below that shown in Table XIX

EVALUATION OF ADHESIVE BONDING TECHNIQUES

In Phase I of this program, difficulties were encountered in obtaining good core-to-face sheet bonds (Refer to TESTING OF SCREENING COMPOSITES). Aluminum core-to-titanium face sheet bond strengths, in particular, were very low. A preliminary analysis of possible causes of poor bond strength showed

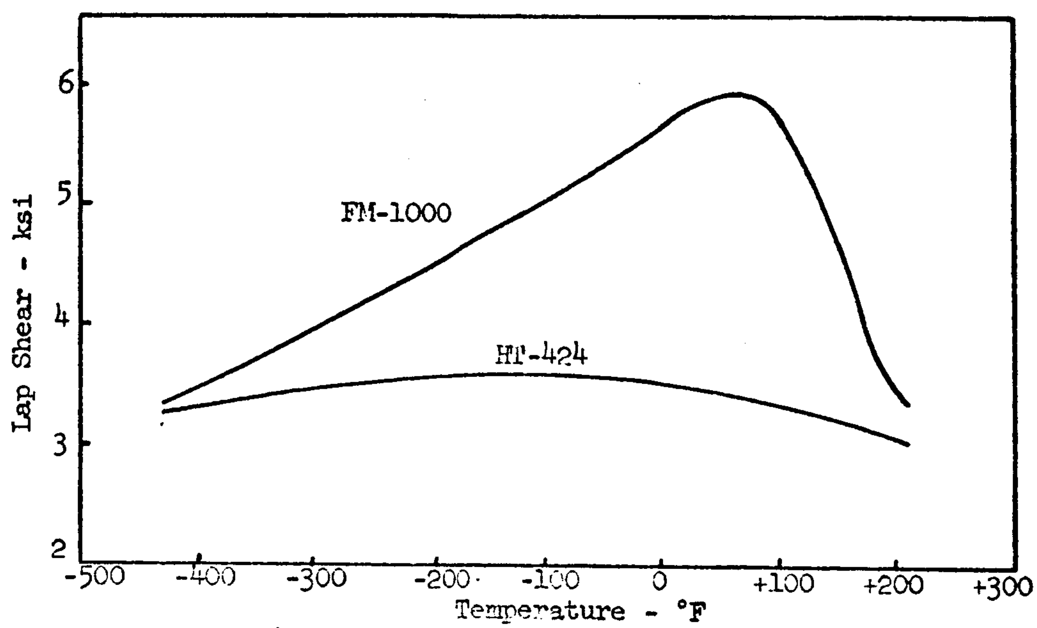


FIGURE 16. ADHESIVE SHEAR STRENGTHS (Bonded to Aluminum)

the following factors to be significant:

1. Cleaning Techniques - The lightweight metal cores used in the specimens were not effectively cleaned by hot vapor degreasing.

This was attributed to the fact that the lightweight core tended to heat rapidly in the hot vapors, and sufficient vapor condensation was thus prevented from occurring, which is necessary for proper cleaning. Titanium alloys are, typically, difficult to bond with consistently high strengths. It is considered that cleaning can be the determining factor in obtaining good bonds.

2. Adhesive Bondline Weight - Adequate adhesive filleting, necessary for good face-to-core bond strength, is dependent to a considerable degree on having sufficient adhesive bondline weight.

A minimum effort evaluation was conducted to (1) investigate methods of cleaning that would result in improved core-to-face sheet bonds, and (2) investigate the effect of adhesive weight. The evaluation was initiated with a screening phase in which metal-to-metal shear specimens were fabricated using potential cleaning techniques for both core and face sheet materials. Cleaning methods were then selected based on strength, process simplicity, and reproducibility. Finally, the selected cleaning methods were applied to core and face sheets in the fabrication of flatwise tension specimens, in which various adhesive bondline weights were used. All the specimens were tested at room temperature.

The following cleaning methods were investigated:

1. Aluminum Face Sheets - NAA/LAD Process Specification LA0110-006, consisting of solvent degreasing followed by hot sodium dichromate sulfuric acid etch.

2. Titanium Face Sheets -

   a. NAA/LAD Process Specification LA0110-006, consisting of alkaline cleaning followed by inhibited hot hydrofluoric acid pickle and hot phosphate etch.

   b. Alkaline cleaning followed by cold hydrofluoric acid-orthophosphoric acid etch.

3. Aluminum Core -

   a. Toluene wash followed by methyl ethyl ketone spray.

   b. Ultrasonic cleaning in methyl ethyl ketone.

Based on lap shear tests on the face sheet metals, the following materials were used in making core to face bonds in flatwise tension specimens:

1. Aluminum Face Sheets - NAA/LAD Process Specification LA0110-006.
2. Titanium Face Sheets - Alkaline cleaning followed by cold hydrofluoric acid-orthophosphoric acid etch.
3. Aluminum Core - Toluene wash followed by methyl ethyl ketone spray.

Flatwise tension specimens of aluminum face sheets-to-aluminum core were prepared using bondline weights of 0.06, 0.09 and 0.12 psf of FM-1000 adhesive, and the cleaning methods established above. In all cases, 100 percent core failures were obtained in the tests. An adhesive bondline weight of 0.09 psf was considered to be the best compromise weight. This weight was then used to prepare flatwise tension specimens of titanium face

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sheets-to-aluminum core. Typical, 100 percent core failures were also obtained with these specimens.

The aluminum core cleaning procedure was also shown to be effective for titanium core. Three flatwise tension specimens of titanium face sheets-to-titanium core were prepared, using this core cleaning method and the preferred titanium face sheet cleaning method. Three-pcf titanium core, 1/4 inch cell size, was bonded to titanium face sheets with FM-1000 adhesive, using a bondline weight of 0.09 psf. In all tests, cohesive bond failures were obtained, i.e., parting of the adhesive itself, indicating good adhesion to the face and core.

OPTIMUM COMPOSITE TEST PLAN

The Phase II test plan for the optimum composites outlined below was submitted to, and approved by NASA/MSFC. Tests were conducted on the selected composite configuration described in Table XVII, and on honeycomb core materials and face sheets used in the configurations. Unless otherwise noted, specimens were tested by NAA/LAD at room temperature, +212°F, -109°F and -320°F, and by NASA/MSFC at -423°F. Three specimens were fabricated by NAA/LAD for each test condition, but generally only two were tested if the first two results agreed closely.

The following tests were conducted in Phase II:

1. Edgewise Compression and Flatwise Tension

   Four composite configurations, Table XVII (Configuration No.4, HF fuel, not tested at -423°F).

2. <u>Flatwise Compression and Core Shear</u>

Materials: 5052-H39 Aluminum Honeycomb, 4.4 pcf

Ti-75A Honeycomb, 4.4 pcf

HRP Glass Honeycomb, 8 pcf (more readily available than the 9-pcf core used for weight comparison in Table XIX).

Core Depth: One inch for flatwise compression

1/2 inch for core shear

3. <u>Facing Tension</u>

Metallic face sheets tested at room temperature only (omitted when supplier or NAA certification test data were available). Glass and aluminum + wire composite face sheets tested (hoop direction) at all temperatures.

TEST METHODS

Details on the testing methods and test specimens are given in Appendix D .

OPTIMUM COMPOSITE TEST RESULTS

FACING TENSION

The results of tension tests on the optimum composite face sheet materials are presented in Table XX and in Figures 17 and 18. Points indicated in all figures are averages of the data. Only the composite facing materials (glass fiber and aluminum + wire) were tested over the range of temperatures, since strength vs temperature data are available from the literature on the monolithic metal face materials.

The first aluminum + wire test specimen fabricated had 3/4 inch wide test sections. In order to conserve material, later specimens made and tested at NAA from 212 F to -320 F had test section one-half inch wide. Facilities for testing at -423 F at NASA/MSFC necessitated the use of a third type of specimen. Specimen blanks approximately 1 1/4 inches wide were sent to MSFC where dumbell type specimens with reduced test sections approximately one half inch wide were made by Eloxing. The one-half inch wide specimens made at NAA were machined. It is believed that the Eloxing results in less damage to the wires at the edge of the specimen and, hence, gives more accurate data. The 3/4 inch specimens made at NAA were machined but it is believed that the greater width may have compensated for any edge damage. The effect of specimen geometry and preparation is further discussed under FAILURE ANALYSIS. The strengths of the glass fiber sheet are plotted versus temperature in Figure 18. The falling off of strength at very low temperatures may be due to lowered ductility in the resin matrix at these temperatures.

FLATWISE TENSION

The results of the flatwise tension tests on the Optimum Composites are presented in Table XXI and in Figure 19. In general the results show higher

TABLE XX
OPTIMUM COMPOSITES
FACING TENSION TESTS

Face Material (1)	Test Temp. (F)	Tension Strength (ksi) Ultimate	Tension Strength (ksi) 0.2% Yield	Modulus of Elasticity (10^6 psi)	Failure Mode
Ti-6al-4V Ann (2)	RT	141.3 Min.	133.5 Min.	Not Determined	-
Ti-6al-4V HT (3)	RT	173.9 Min.	161.1 Min.	Not Determined	-
PH15-7Mo	RT	196.2	190.8	26.6	Test Section failure
	RT	195.8	190.7	26.5	
Aluminum + Wire (Wire direction)	RT (4)	124.3	100.8	12.4	Adhesive bond intact
	RT (4)	123.4	99.2	12.7	
	RT	102.0	101.7	12.1	↑
	RT	89.3	(5)	12.5	
	+212	63.5	(5)	12.2	
	+212	62.5	(5)	12.2	
	-109	132.9	98.8	13.4	Bond shear failure
	-109	124.2	106.0	12.8	
	-320	112.9	109.3	12.8	
	-320	120.0	103.5	13.1	↓
	-423	163.3	(5)	N.D.	Adhesive bond intact
	-423	158.7	(5)	13.6	
Glass Fiber ("2" direction)	RT	98.7	↑	5.4	↑
	RT	92.4	(5)	N.D.	
	+212	75.8		3.6	Sequential fiber failure in test section
	+212	76.2	↓	4.7	

(Continued next page)

TABLE XX (Continued)
OPTIMUM COMPOSITE
FACING TENSION TESTS

Face Material (1)	Test Temp. (F)	Tension Strength (ksi)		Modulus of Elasticity (10^6 psi)	Failure Mode
		Ultimate	0.2% Yield		
Glass Fiber ("2" direction)	-109	160.2	(5)	4.8	Sequential fiber failure in test section
	-109	139.8	(5)	5.1	Sequential fiber failure in test section
	-320	127.5	(5)	5.4	Sequential fiber failure in test section
	-320	147.1	(5)	4.6	Sequential fiber failure in test section
	-423	103.5	(5)	8.4	Sequential fiber failure in test section
	-423	117.8	(5)	10.7	Sequential fiber failure in test section

(1) Refer to TABLE XVII for composite details
(2) Supplier certification data
(3) NAA receiving inspection data
(4) Speciment test width 3/4 inch. Other speciment 1/2 inch wide
Refer to text.
(5) Failed prior to 0.2% yield

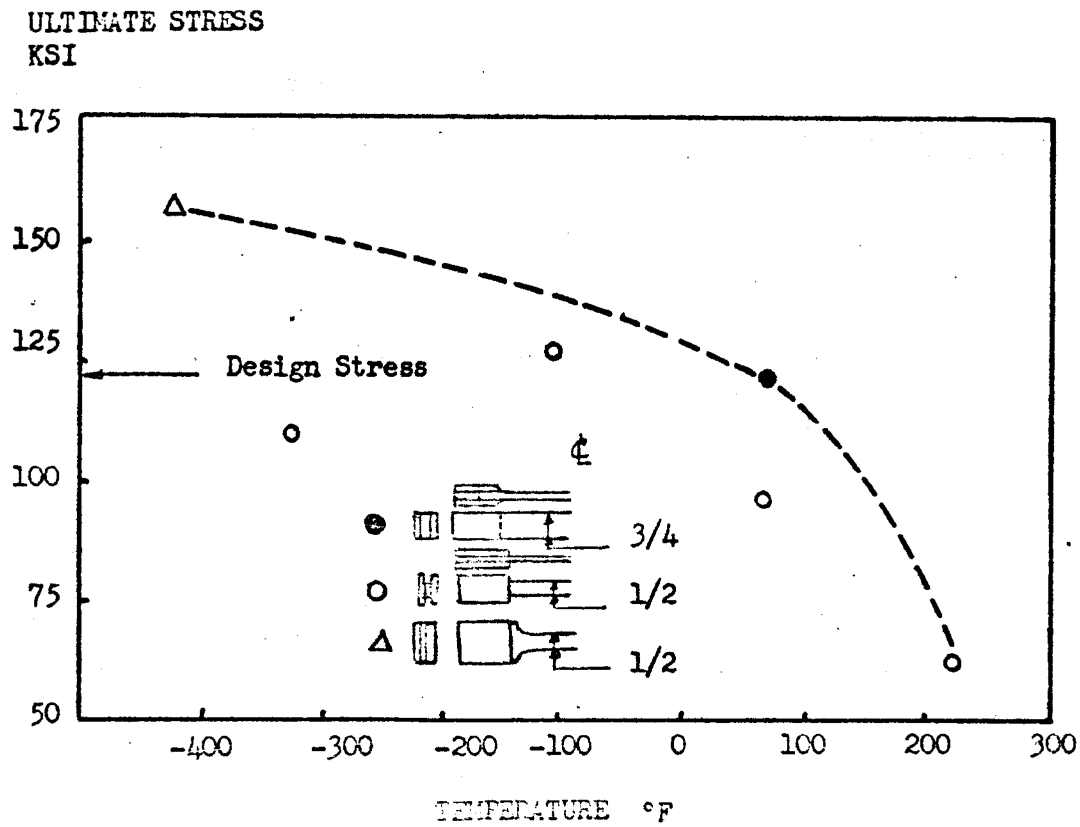


FIGURE 17 ALUMINUM + WIRE SHEET - TENSION TESTS

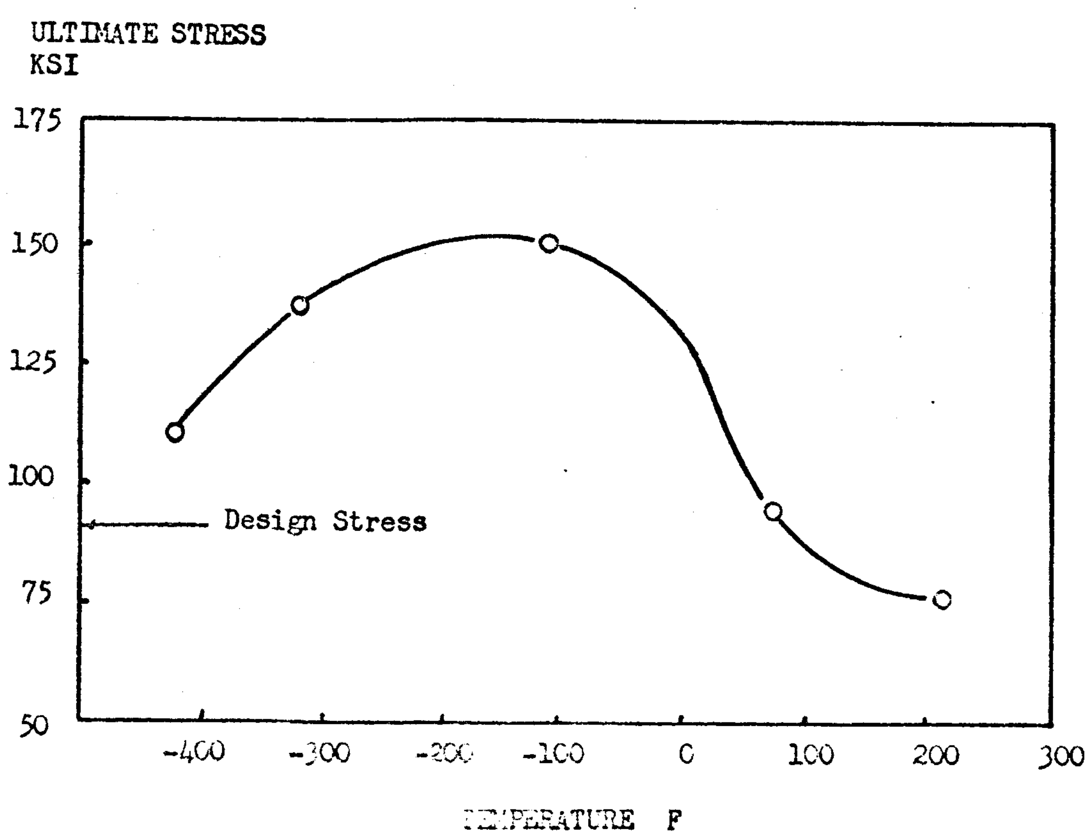


FIGURE 18 GLASS FIBER SHEET - TENSION TESTS

TABLE XXI
OPTIMUM COMPOSITES
FLATWISE TENSION TESTS

Config. No. (1)	Test Temp. (F)	Ultimate Strength (psi)	Failure Mode
1	RT	753	
	RT	779	
	+212	628	
	+212	320	
	-109	828	Cohesive failure in HT-424
	-109	911	
	-320	780	
	-320	792	
	-423	850	
	-423	984	
	-423	1058	
2	RT	420	Face sheet interlaminar failure (2)
	RT	357	
	RT	638	
	RT	520	
	+212	657	Cohesive failure in HT-424
	+212	664	
	+212	292	67% cohesive, 33% adhesive (3)
	-109	116	50% cohesive, 50% adhesive (3)
	-109	1168	
	-109	1033	
	-109	521	Cohesive failure in HT-424
	-320	960	
	-320	929	
	-320	1008	
	-423	960	
	-423	1200	
	-423	374	Adhesive failure at glass face

(Continued next page)

TABLE XXI (Continued)
OPTIMUM COMPOSITES
FLATWISE TENSION TESTS

Config. No. (1)	Test Temp. (F)	Ultimate Strength (psi)	Failure Mode
3	RT	875	Al Core to FM-1000 adhesive failure at aluminum foil
	RT	523	
	RT	495	
	RT	313	
	+212	58	Adhesive bond failure at titanium face
	+212	46	
	-109	769	Cohesive failure at aluminum foil
	-109	898	
	-320	526	Adhesive bond failure at titanium face
	-320	626	
	-423	553	Not determined
	-423	33	
	-423	857	
4	RT	927	95% adhesive failure at core 5% core failure
	RT	837	
	+212	159	Adhesive bond failure at core
	+212	96	
	-109	1359	100% core failure
	-109	1245	
	-320	1719	
	-320	1554	

(1) Refer to TABLE XVII for configuration details
(2) Defective glass fiber face. Refer to text
(3) Core to HT-424 adhesive failure

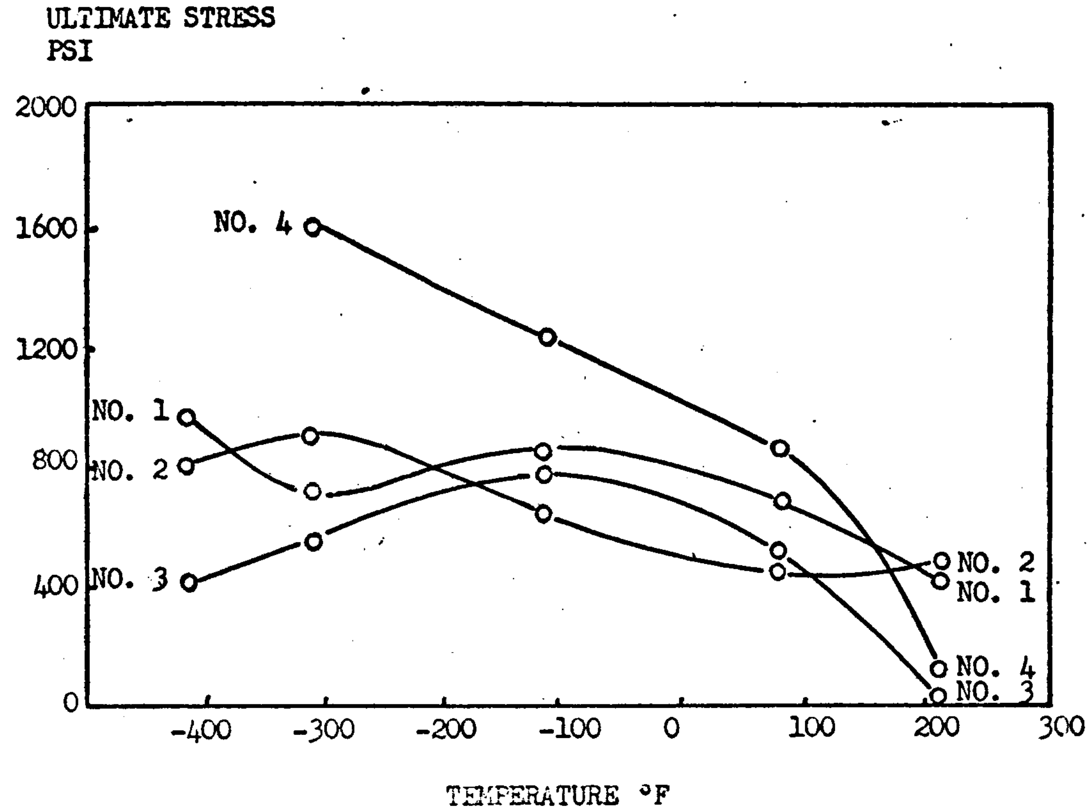


FIGURE 19 OPTIMUM COMPOSITE - FLATWISE TENSION

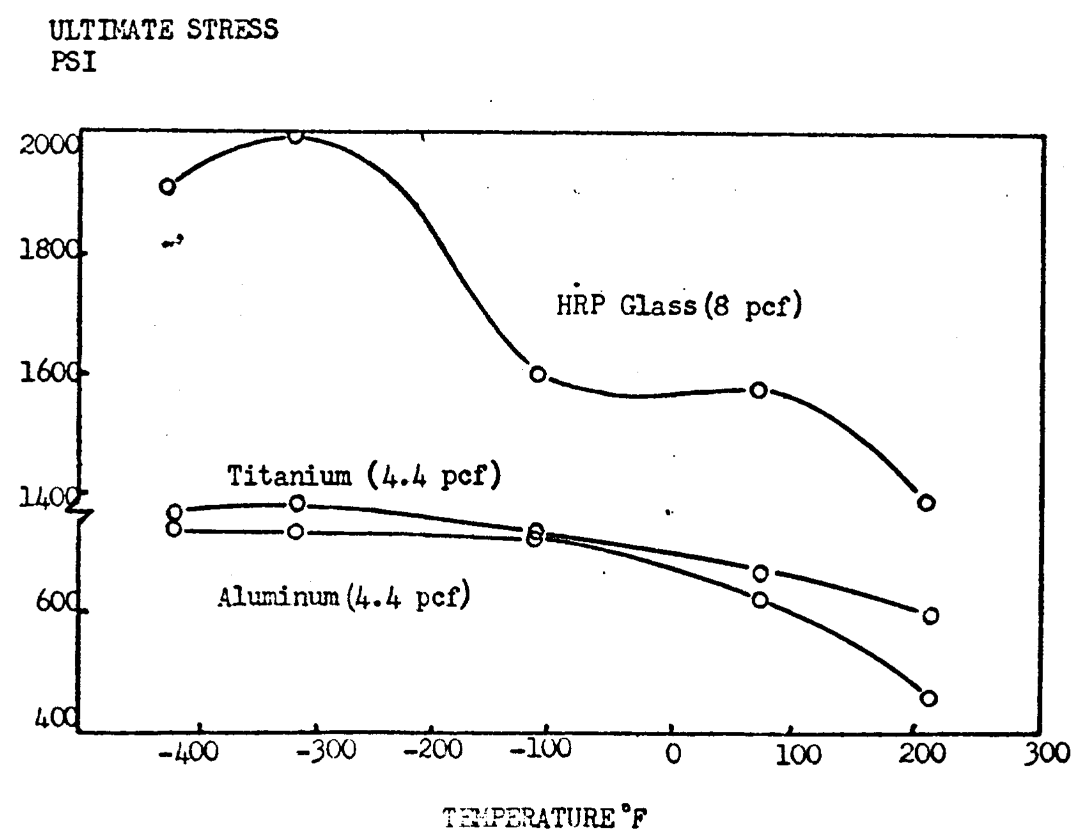


FIGURE 20 HONEYCOMB CORES - FLATWISE COMPRESSION

adhesive bond strengths than were obtained in the flatwise tension tests on the Screening Composites, due to the improved prebonding cleaning methods employed. However, some scatter in the results was still obtained.

Configuration No's. 3 and 4, which were fabricated first, were bonded with FM-1000 adhesive. After the very low flatwise tension results at 212 F on these two configurations were noted, a change was made to the HT-424 in Configuration No's. 1 and 2. Much higher strengths were obtained in the HT-424 bonds at 212 F than in the FM-1000 bonds. However, the highest test values were obtained in Configuration No. 4 at -109 and -320 F where the FM-1000 to PH15-7Mo bonds were strong enough to cause core failure.

CORE FLATWISE COMPRESSION

The results of flatwise compression tests on the honeycomb cores used in the optimum composites are presented in Table XXII. It should be noted that the cell walls of the titanium core were in a partially buckled condition as received from the supplier. The ultimate compression strengths of the cores are plotted versus temperature in Figure 20.

The first two room temperature tests on Configuration No. 2 were on a panel with defective glass fiber faces. This panel was discarded and a new panel was fabricated and used for the balance of the tests on this configuration.

Results of the flatwise tension tests are illustrated and further discussed in the section FAILURE ANALYSIS.

CORE SHEAR

The results of shear tests on the honeycomb cores used in the optimum composites are presented in Table XXIII. Plots of the strengths and moduli versus temperature are shown in Figures 21 and 22, respectively. HT-424

TABLE XXII

HONEYCOMB CORES

FLATWISE COMPRESSION TESTS

Material (1)	Test Temp. (F)	Ultimate Strength (psi)	Modulus (10^6psi)	Failure Mode
Aluminum Honeycomb				Core buckling
	RT	636	0.160	
	RT	595	0.154	
(5052-H39 4.4 pcf)	+212	435	0.172	
	+212	430	0.138	
	-109	647	0.173	
	-109	798	0.213	
	-320	726	0.189	
	-320	736	0.239	
	-423	690	Not determined	
	-423	765		
	-423	740		
Glass Honeycomb	RT	1581	0.150	Core buckling
	RT	1590	0.144	
(HRP, 8 pcf)	+212	1430	0.116	
	+212	1350	0.096	
	-109	1666	0.295	
	-109	1525	0.435	
	-320	2060	0.194	
	-320	2140	0.194	
	-423	1805	Not determined	
	-423	1987		
	-423	1865		

(Continued next page)

TABLE XXII (Continued)

HONEYCOMB CORES

FLATWISE COMPRESSION TESTS

Material (1)	Test Temp. (F)	Ultimate Strength (psi)	Modulus (10^6psi)	Failure Mode
Titanium Honeycomb (Ti-75A, 4.4 pcf)	RT	818	0.093	Core buckling
	RT	584	0.075	
	+212	618	0.055	
	+212	661	0.055	
	-109	738	0.237	
	-109	740		
	-320	853	0.211	
	-320	758	0.179	
	-423	817	Not determined	
	-423	753		
	-423	705		

(1) Refer to Table XVII for further material description

TABLE XXIII
HONEYCOMB CORES
SHEAR TESTS

Material (1)	Test Temp. (F)	Ultimate Strength (psi)	Modulus (10^4 psi)	Failure Mode
Aluminum honeycomb	RT	339	5.14	Core shear
	RT	308	4.27	Adhesive shear
(5052-H39 4.4 pcf)	+212	129	1.33	Core and adhesive shear
	+212	121	1.72	↓
	-109	328	6.57	Core shear
	-109	341	5.78	↓
	-320	356	6.66	↓
	-320	347	5.98	↓
	-423	465	Not determined See text	↓
	-423	463		↓
	-423	472		↓
Glass honeycomb	RT	634	3.31	Core shear
	RT	643	2.38	↓
(HRP, 8pcf)	+212	129	0.76	Core and adhesive shear
	+212	204	0.83	↓
	-109	659	4.93	Core Shear
	-109	793	5.32	
	-320	656	3.78	Adhesive Shear
	-320	686	4.81	
	-423	416	4.24	Core shear
	-423	417	4.34	↓
	-423	441	3.57	↓
Titanium Honeycomb	RT	373	3.87	↑
	RT	361	3.62	↑
(Ti-75A, 4.4 pcf)	+212	332	2.43	↑
	+212	324	2.43	↑
	-109	381	2.61	Core shear
	-109	356	3.70	↓
	-320	406	3.67	↓
	-320	404	2.66	↓
	-423	463	Not determined See text	↓
	-423	413		↓
	-423	421		↓

(1) Refer to Table XVII for further material description

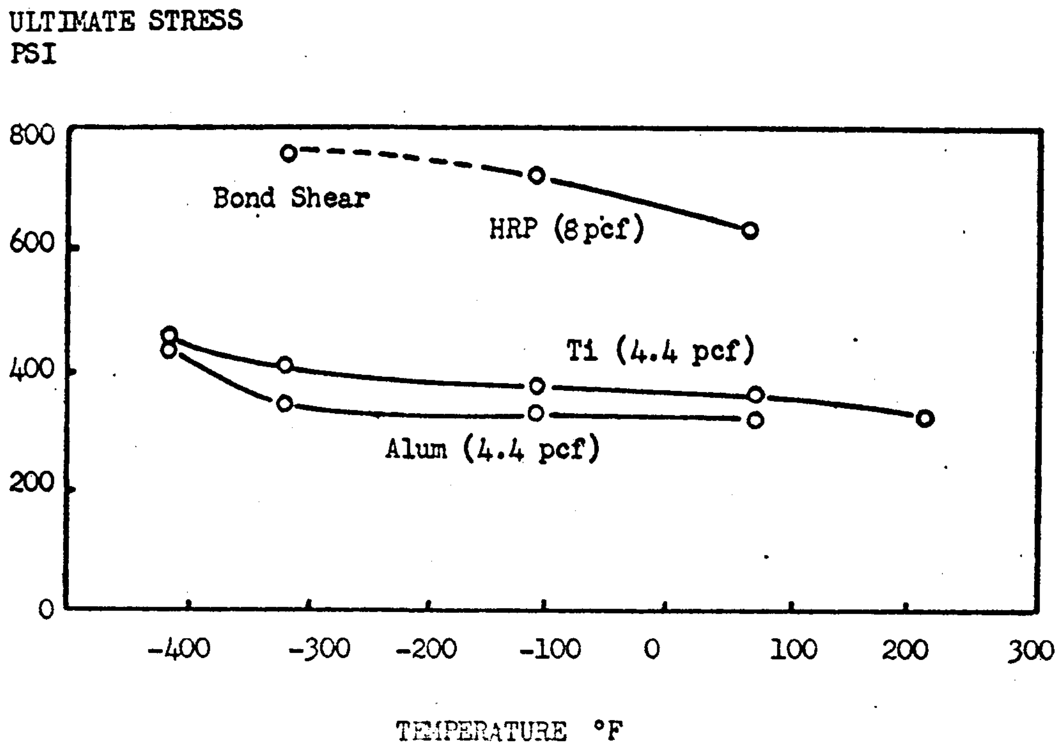


FIGURE 21 HONEYCOMB CORES - SHEAR ULTIMATE

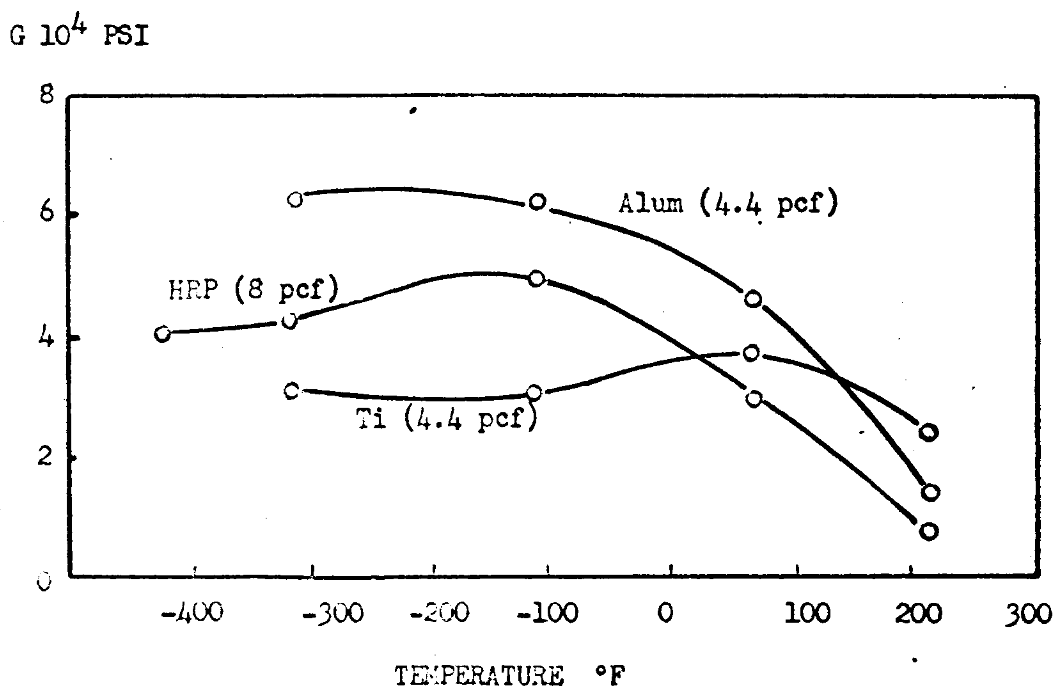


FIGURE 22 HONEYCOMB CORES - SHEAR MODULUS

adhesive was used to bond the titanium core to the shear test block. The HT-424 adhesive bond was sufficiently strong to cause shear failure in the titanium core. FM-1000 adhesive was used to bond the glass and the aluminum cores. In several cases shear failure occurred in the FM-1000 adhesive bond. Points where this occurred are not generally included in Figure 21, since the bond shear may have occurred at a value considerably below that of the core shear. The bond shear value of the HRP glass core at -320 F lies near the straight line extrapolation of the HRP curve and has been indicated.

Low apparent shear modulus in the titanium core may be due to the prebuckled condition in which this material was received from the supplier.

Equipment difficulties were experienced in determining the shear moduli of the aluminum and titanium cores at -423 F and values are, therefore, not reported.

EDGEWISE COMPRESSION

The results of the edgewise compression tests on the Optimum Composites are presented in Table XXIV. Mean values from Table XXIV were used to derive the plots of strength versus temperature for the configurations shown in Figures 23 through 26. In each figure the composite design ultimate compression stress or load is indicated. In Configuration No's. 1, and 4 this design value is considerably lower than the test compression strengths obtained from the composites at room temperature. This results from the fact that the faces of these composites were sized for the 10,000 lb/in hoop load and thus have considerable margin for the 4000 lb/in axial load.

The ultimate stress that could be sustained by the Ti-6Al-4V faces in Configuration No. 1 apparently reached a maximum at about -109 F, Figure 23. Below this temperature the failure stress decreases, although the potential

TABLE XXIV

OPTIMUM COMPOSITES

EDGEWISE COMPRESSION TEST

Configuration (1)	Test Temp. (F)	Ultimate Strength (ksi)	Compression Modulus (10^6 psi)	Failure Mode
1	RT	116.7		
	RT	127.5		
	+212	122.0	Not	Face sheet local
	+212	106.0	Measured	buckling and cohesive bond failure
	-109	180.4		
	-109	173.7		
	-320	153.3		
	-320	160.0		
	-423	150.0		
2	RT (2)	41.4	4.5	Face interlaminar failure
	RT	64.4	6.2	
	RT	69.4	6.7	Face compression failure
	+212	14.4	4.6	
	+212	10.4	4.6	
	+212	8.2	3.5	
	-109	29.7	-	Face interlaminar failure
	-109	60.8	8.1	
	-109	56.7	10.5	Face compression failure
	-320	79.7	6.3	
	-320	64.6	6.2	
	-320	73.0	6.6	
	-423	43.9	6.1	
	-423	48.8	3.3	
	-423	53.4	-	

(Continued next page)

TABLE XXIV (Continued)

OPTIMUM COMPOSITES
EDGEWISE COMPRESSION TEST

Configuration (1)	Test Temp. (F)	Ultimate Strength (ksi)	Compression Modulus (10^6 psi)	Failure Mode
3				
Ti Face Al-Wire Face	RT	134.2 38.2	17.6 5.02	Al-Wire face sheet buckling
Ti Face Al-Wire Face	RT	132.7 38.0	19.2 5.50	Al-Wire face sheet buckling
Ti Face Al-Wire Face	+212	74.5 21.3	18.1 5.18	Core to adhesive bond failure Al-Wire delamination
Ti Face Al-Wire Face	+212	57.0 17.6	14.9 4.6	Core to adhesive bond failure Al-Wire delamination
Ti Face Al-Wire Face	-109	185.8 53.0	21.0 6.00	Titanium face sheet-to-adhesive bond failure
Ti Face Al-Wire Face	-109	166.9 48.0	21.6 6.19	Titanium face sheet-to-adhesive bond failure
Ti Face Al-Wire Face	-320	150.6 43.0	23.4 6.70	Al-Wire face sheet-to-adhesive bond failure
Ti Face Al-Wire	-320	132.2 37.8	22.2 6.4	Al-Wire face sheet-to-adhesive bond failure. Al-wire delamination
Ti Face Al-Wire Face	-423	103. 45.4	↑ Not determined	Al-Wire delamination
Ti Face Al-Wire Face	-423	109 48.4	↓	Al-Wire delamination
4	RT RT	184.8 195.1	25.6 29.7	Core failure adjacent to face sheet; face sheet buckling
	+212 +212 +212	94.2 102.9 53.2	 30.5 29.8	Bond failure Face sheet buckling Bond failure
	-109 -109	169.6 210.2	30.2 23.5	Face sheet buckling
	-320 -320	238.5 243.7	29.8 28.6	Face to adhesive bond failure

(1) Refer to Table XVII for configuration details

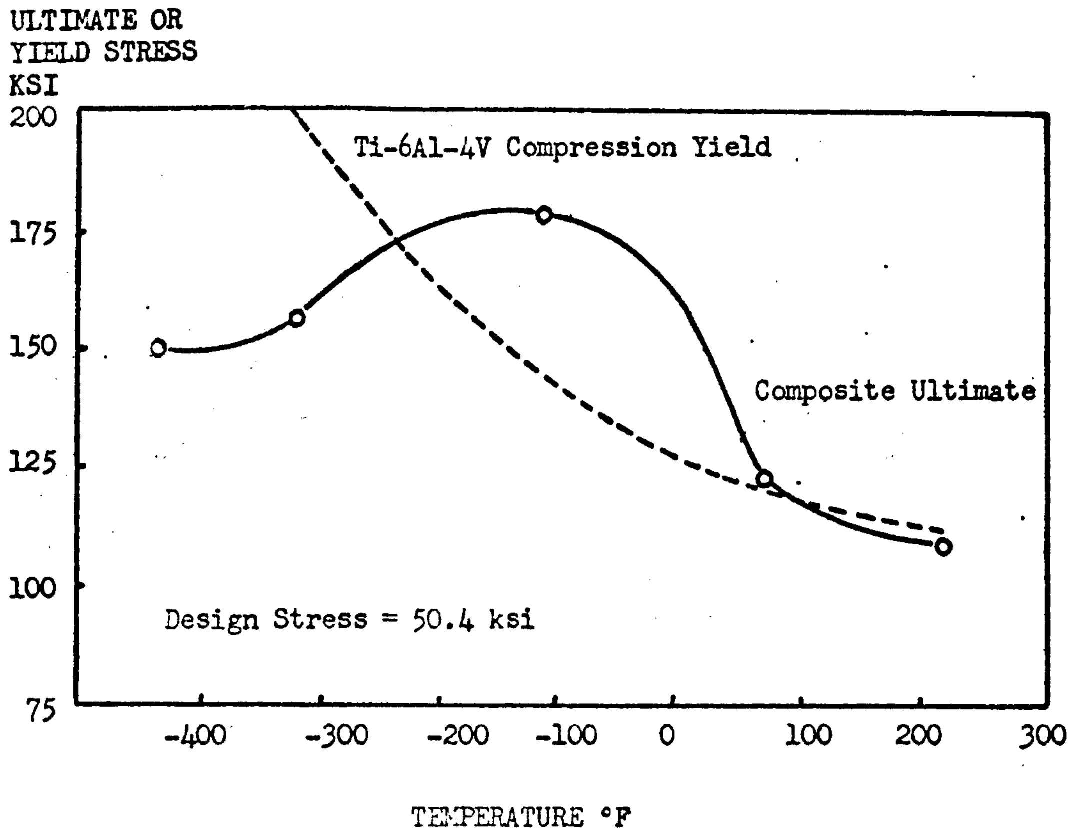


FIGURE 23 OPTIMUM COMPOSITE NO. 1 (Titanium Ann)-
EDGEWISE COMPRESSION

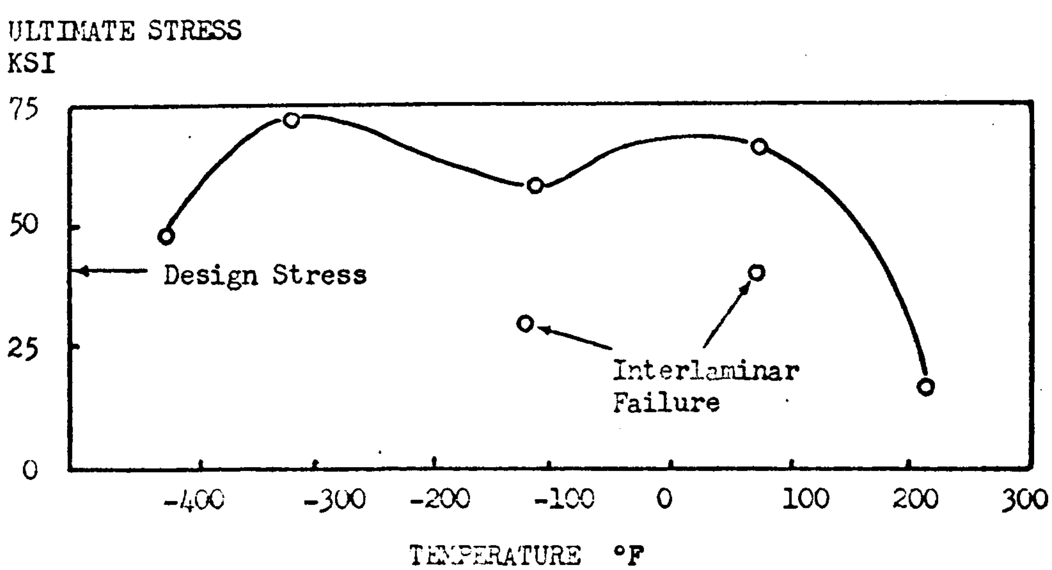


FIGURE 24 OPTIMUM COMPOSITE NO. 2 (Glass Fiber)
EDGEWISE COMPRESSION

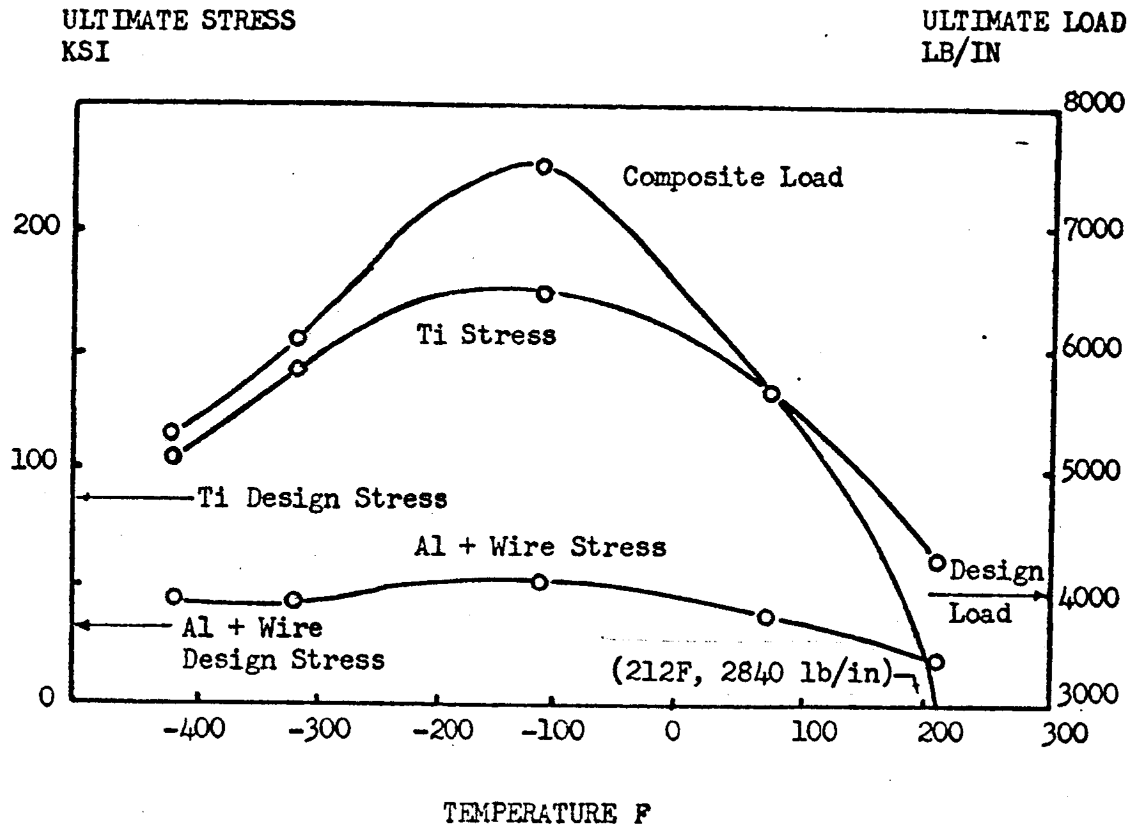


FIGURE 25 OPTIMUM COMPOSITE NO. 3 (Ti HT & Al+Wire)
EDGEWISE COMPRESSION

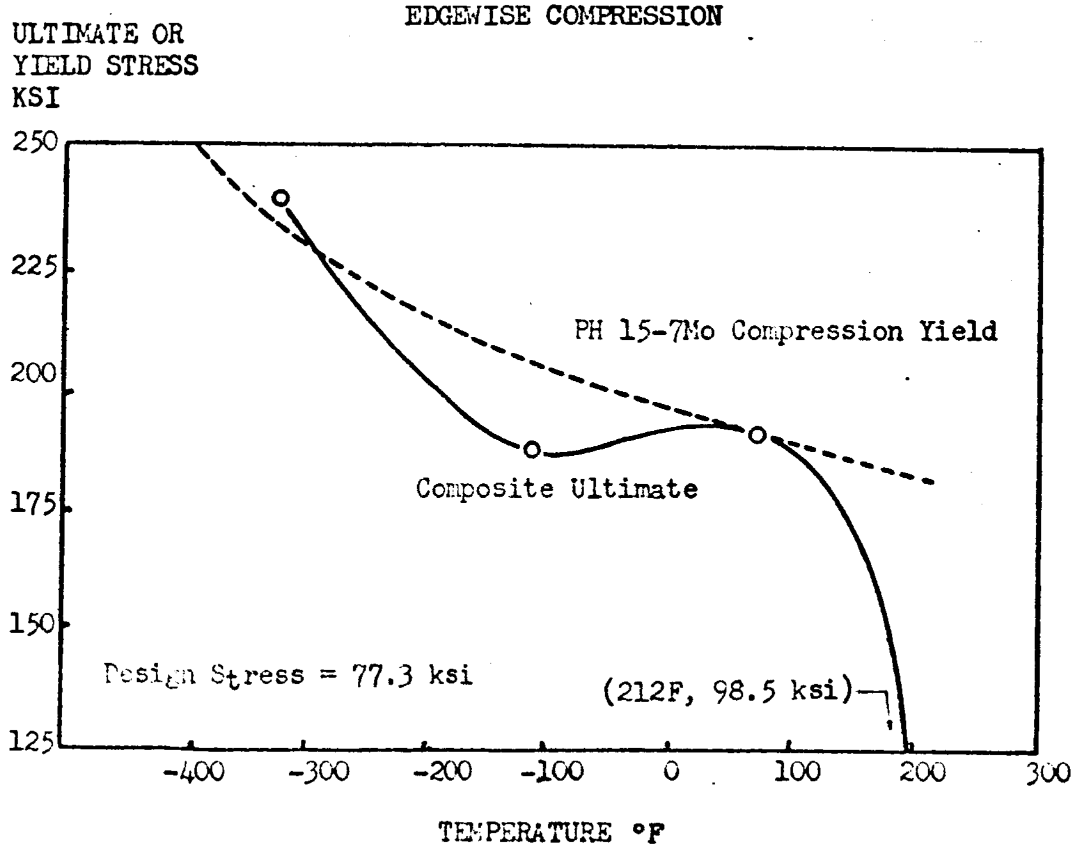


FIGURE 26 OPTIMUM COMPOSITE NO. 4 (PH15-7Mo)
EDGEWISE COMPRESSION

yield strength of the titanium faces continually increases with decreasing temperature. The difference in the shapes of the curve of composite face stress and the curve of titanium material yield strength between room temperature and -240 F is not readily explainable. A possible explanation is that the yield curve represents approximately minimum allowable properties, whereas, the actual strengths of the composite faces at these temperatures may be above minimums.

The decreasing strength of the Configuration No. 1 composite above about -109 F may be explained by reduced ductitlity in the HT-424 face-to-core adhesive at these temperatures which prevented it from deflecting with the metal without failing.

Configuration No. 2, the glass fiber faces of which were sized for the axial design load, had a positive margin of strength at room temperature and below when the failure mode in the face sheet was compressive, Figure 24. Interlaminar mode of failure in the faces significantly reduced the failure stress. The reduction in failure stress at temperatures above room temperature is probably due to loss of strength in the 828 resin matrix, which is not a heat resistant system. Reduction in failure stress below -320 F may be due to reduced ductility in the resin matrix and/or the HT-424 face-to-core adhesive at these temperatures. Unfortunately, there are no data available in the literature on the compressive strength of thin non-woven glass sheets to compare with the results of these tests.

Failure load (not shown in Table XXIV) as well as failure stress is shown for Configuration No. 3, which had unlike faces, Figure 25. Configuration No. 3 had a positive margin of strength in both face sheets. This margin is small in the aluminum + wire face due to its relatively low axial compressive yield (refer to Table XVII). Reduction in failure stress below -109 F may be explained by reduced ductility in the FM-1000 face-to-core adhesive at these temperatures (compare with the results on Configuration No. 1). The sharp reduction in strength at 212 F is due to the greatly reduced strength of the FM-1000 adhesive at this temperature (refer to FLATWISE TENSION).

It will be noted in comparing Figures 23 and 25 that somewhat higher stresses were obtained in annealed than in heat treated titanium. At most temperatures prior failure in the aluminum + wire face prevented higher stressing of the titanium face (refer to Table XXIV).

Configuration No. 4 was the only composite that sustained stresses below -109 which were comparable with the potential strength of the composite face material at these temperatures, Figure 26. This may be due to the exceptionally high face-to-core bond strengths achieved in this composite (refer tc FLATWISE TENSION). The low strength at 212 F is due, as in Configuration No. 3, to the low strength of the adhesive at this temperatures.

The results of the edgewise compression tests are discussed further in the section FAILURE ANALYSIS.

FAILURE ANALYSIS

FACING SHEET TENSILE TESTS

GLASS FIBER IN RESIN

Two types of ultimate failure modes occurred in the tensile tests on glass fiber composite face sheet specimens. These were discussed previously in the section FABRICATION AND TESTING OF COMPOSITE SHEET and are illustrated in Figure 27. When failure occurred near or in the end grips or at some other point of stress concentration, the fracture was generally sharp and well defined. Test values obtained from this type of failures tended to be scattered. Failure in the test area, away from the grips, occurred as a "sequential" fiber failure. Typically, a few fibers would first break near the specimen edge and then the fracture would progress from fiber to fiber, each fiber generally shredding away from the specimen body as it broke. The broken specimen, therefore, consisted of a brushlike mass. This type of failure generally produced more uniform strength values.

The failures illustrated in Figure 27 are characteristic of those obtained at all test temperatures.

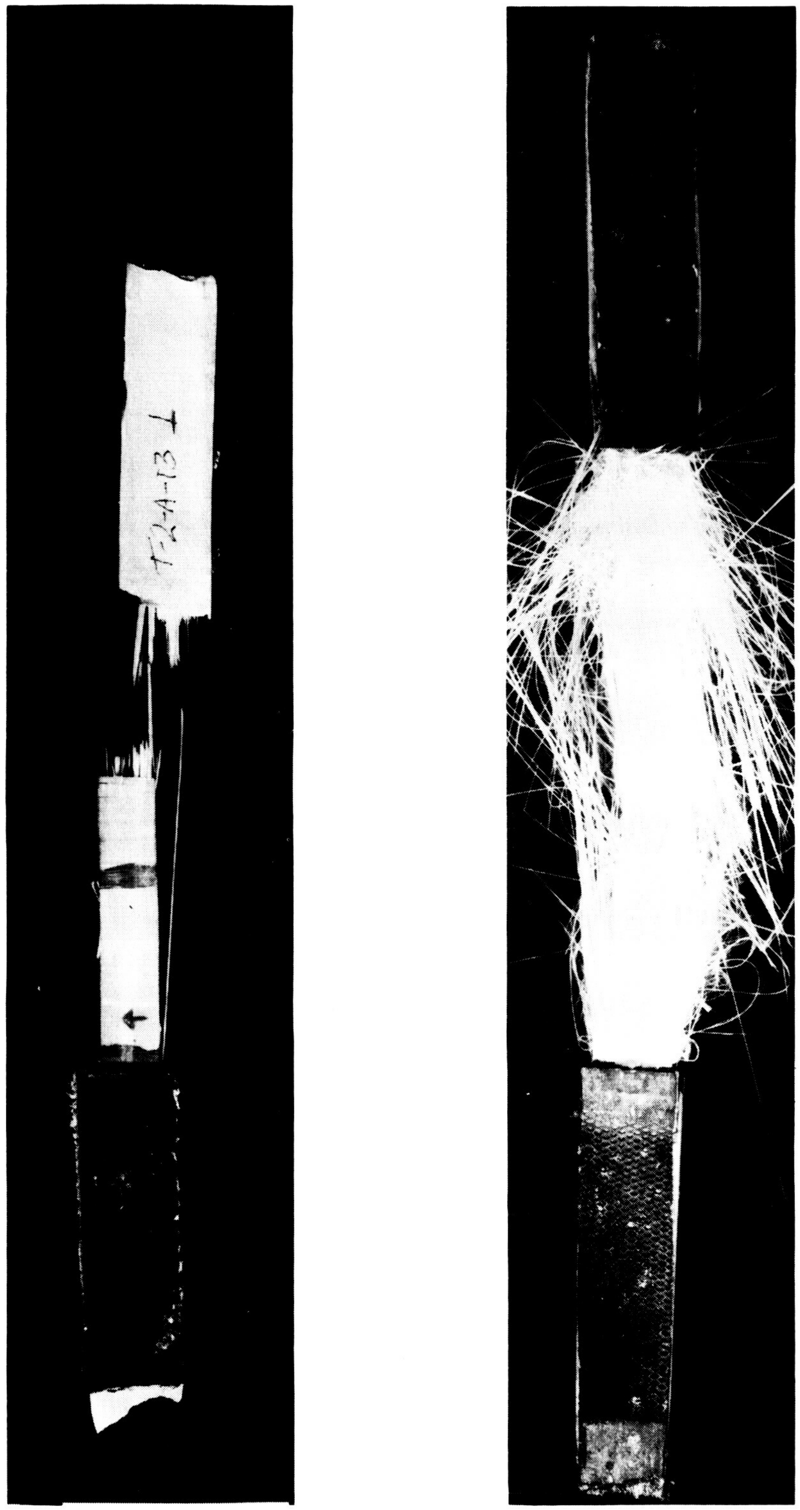
STEEL WIRE IN PLASTIC

Failures in the wire-plastic sheets were also discussed in the previous section on fabrication and testing of composite sheet. Some typical failures were shown in Figure 28. As in the case of the glass fiber sheets failure in or near the grips in the wire-plastic specimens tended to produce erratic results. However, all failures in the wire-plastic sheets, regardless of location, were sharply defined, appearing similar to fractures obtained in tensile tests of brittle monolithic metals, with little or no tendency to shredding of the wires.

Sheet No. 11
106.1 ksi

Sheet No. 8
138.1 ksi

Failure
Near Grips

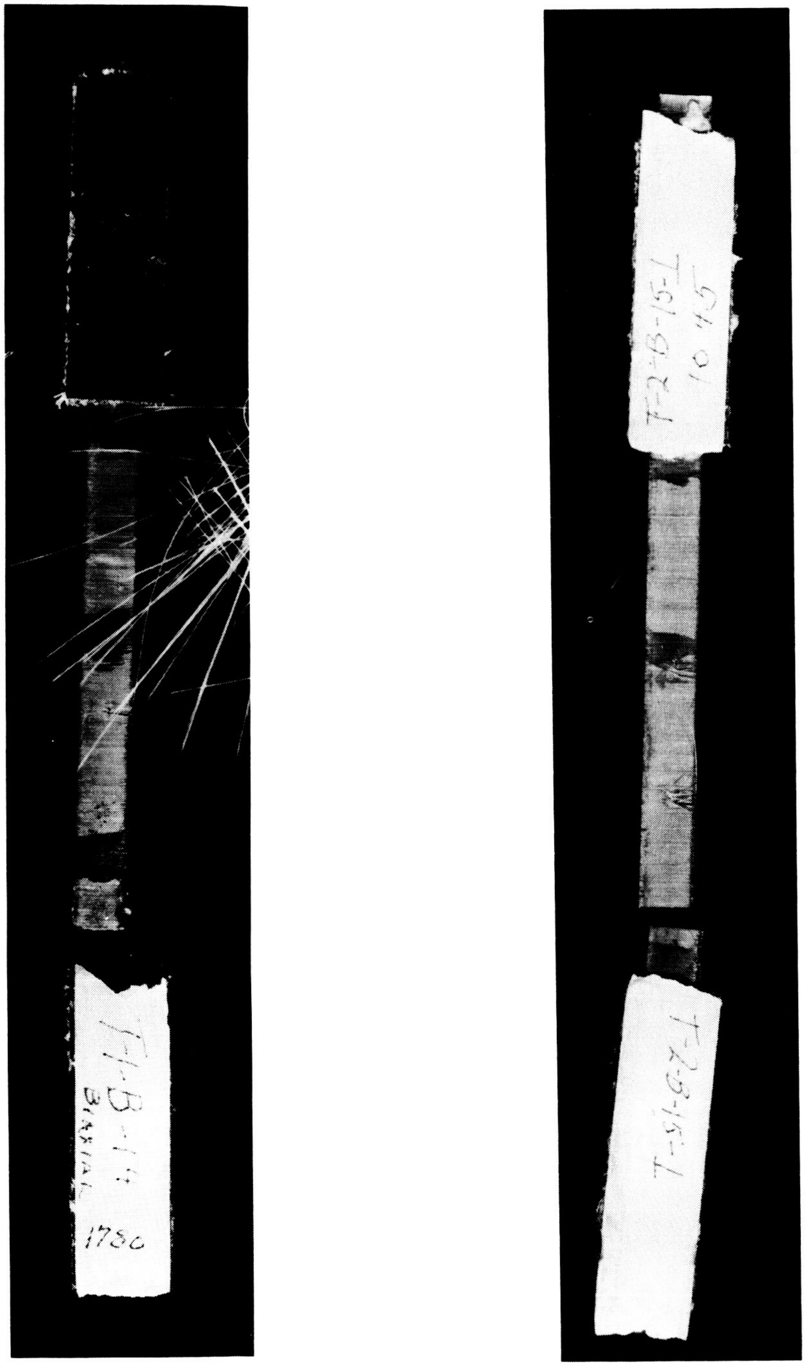


Test Area
Failure

FIGURE 27 GLASS FIBER SHEET TENSION SPECIMENS

Sheet No. 12
129.9 ksi

Sheet No. 13
102.5 ksi



Failure
in Grips

Test Area
Failure

FIGURE 28 WIRE SHEET TENSION SPECIMENS

ALUMINUM + WIRE

Failure modes in the aluminum + wire composite sheets were apparently influenced both by the nature of the adhesive bond and by the test specimen design. A summary of the failure modes is given in Table XXV.

TABLE XXV
ALUMINUM WIRE SHEETS
FAILURE ANALYSIS

Reference Table (1)	Wire Dia (In.)	Adhesive Sheet Thickness (In.)	Specimen Width (In.)	Test Temp. (F)	Failure Mode in Adhesive Bond
VI	.004	.003 .005	3/4	RT	Bond intact
XVI	.004	.001	3/4	RT	Bond failure
XVI	.015	.003	3/4	RT	Bond intact
XX	.015	.003	3/4	RT	Bond intact
XX	.015	.003	1/2	ALL	Bond failure (2)

(1) Table reporting the test data.

(2) Bond intact at -423 F (See OPTIMUM COMPOSITE TEST RESULTS).

In some specimens where bond failure between the wires and aluminum occurred, none of the wires broke. In others where bond failure occurred only some of the wires broke. When the bond remained intact, failure of all the wires was simultaneous with failure in the aluminum. In all of the three-quarter inch wide test specimens where .003 inch or thicker sheets of adhesive were used, the adhesive bond between the aluminum sheets and the steel wires remained intact through the failure. Typical specimens with the bond intact are shown in Figures 29 and 30. These examples both had .003 inch or thicker adhesive sheets. The configuration No. 1 aluminum + wire composite sheets, the test results of which were reported in Table XVI,

Wire Diameter .004 in.
Adhesive Sheet Thickness .005 in.

Specimen Width 3/4 inch
Test Temperature R. T.

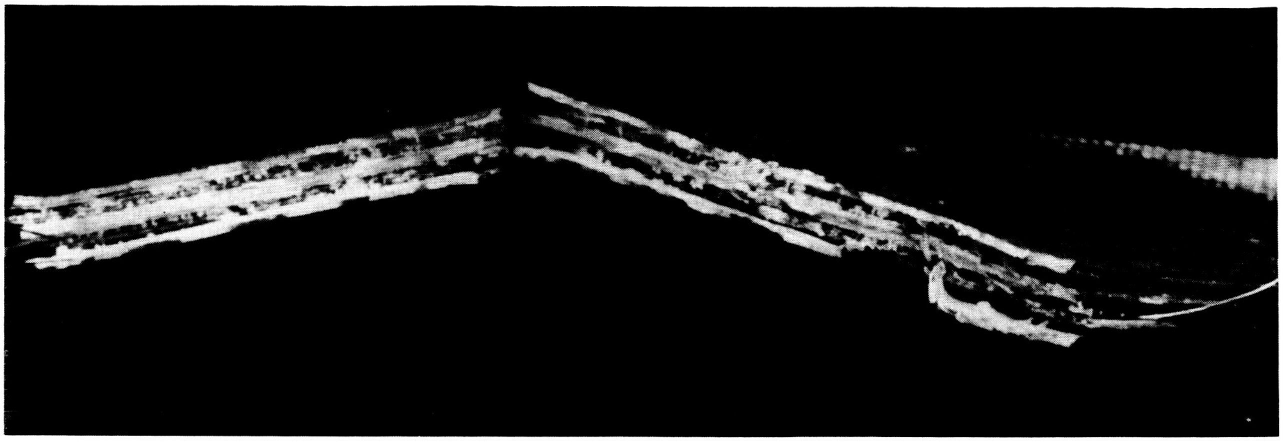


FIGURE 29 ALUMINUM + WIRE COMPOSITE TENSION SPECIMEN
ADHESIVE BOND INTACT

Wire Diameter .015 inch
Adhesive Sheet Thickness .003 inch

Specimen Width 3/4 inch
Test Temperature R.T.

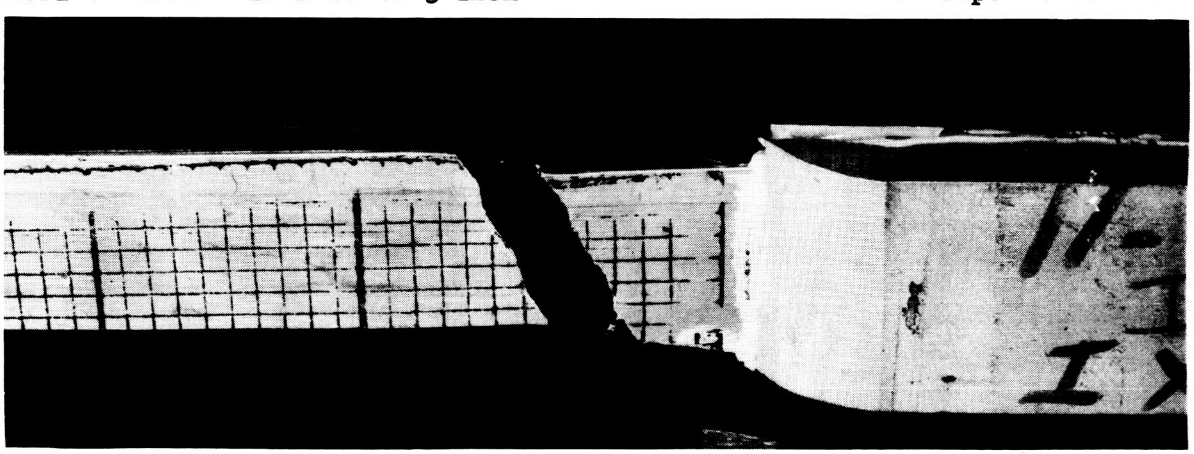


FIGURE 30 ALUMINUM + WIRE COMPOSITE TENSION SPECIMEN
ADHESIVE BOND INTACT

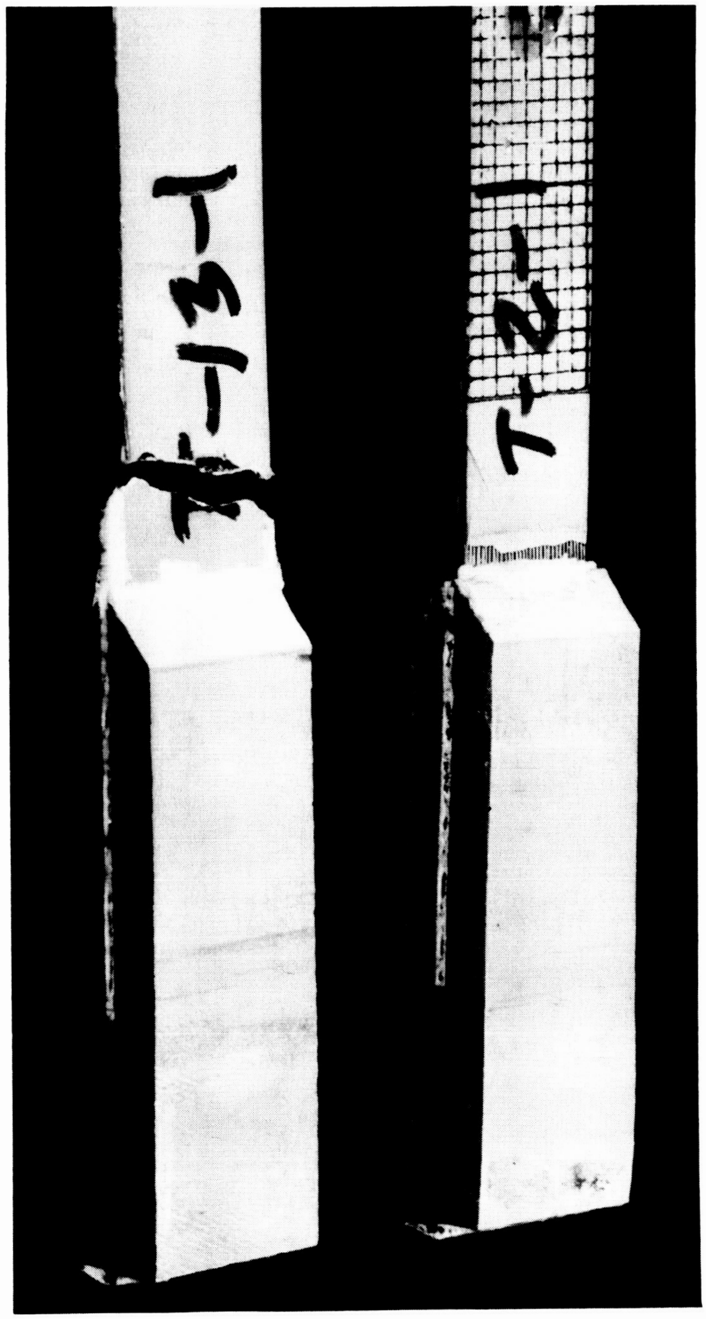
failed in the bond between the wires and the outer aluminum sheet. This bond failure, which is illustrated in Figure 31, may be attributable to the small amount of adhesive used, in this case .001 inch sheets. In Figure 32 are shown typical adhesive bond failures in test specimens with a reduced (one-half inch) width. The extreme shearing in the bond in the 212 F specimen is undoubtedly attributable to low strength in the FM-1000 adhesive at this temperature. Some bond shear failure was noted in the one-half inch wide specimens tested at RT through -320 F.

FLATWISE TENSION TESTS

The FM-1000 adhesive showed a greater tendency than the HT-424 adhesive to an "adhesive" type of failure (failure at the bonding surface) when bonded to titanium or aluminum. Figure 33 and Figure 34 show "adhesive" type failures between FM-1000 and a titanium face and between FM-1000 and an aluminum core, respectively.. "Adhesive" failures were obtained also between FM-1000 and aluminum core at room temperature and between FM-1000 and titanium face sheets at -320 F. HT-424 joints failures were principally of the "cohesive" type (failure within the adhesive itself). Typical "cohesive" failures in the HT-424 bond between titanium core and titanium face sheet and between aluminum core and glass fiber face sheet are shown in Figures 35 and 36, respectively. The HT-424 adhesive can be seen adhering to both core and facings in the illustration. Similar "cohesive" failures generally were obtained in HT-424 at other test temperatures.

The FM-1000 adhesive exhibited "cohesive" failure between the glass fabric core and the aluminum foil, Figure 37. Also, the FM-1000 was sufficiently strong to cause 100 percent failure in aluminum core at -109 F

Configuration
No.2 (Fig.13)
105.7 ksi

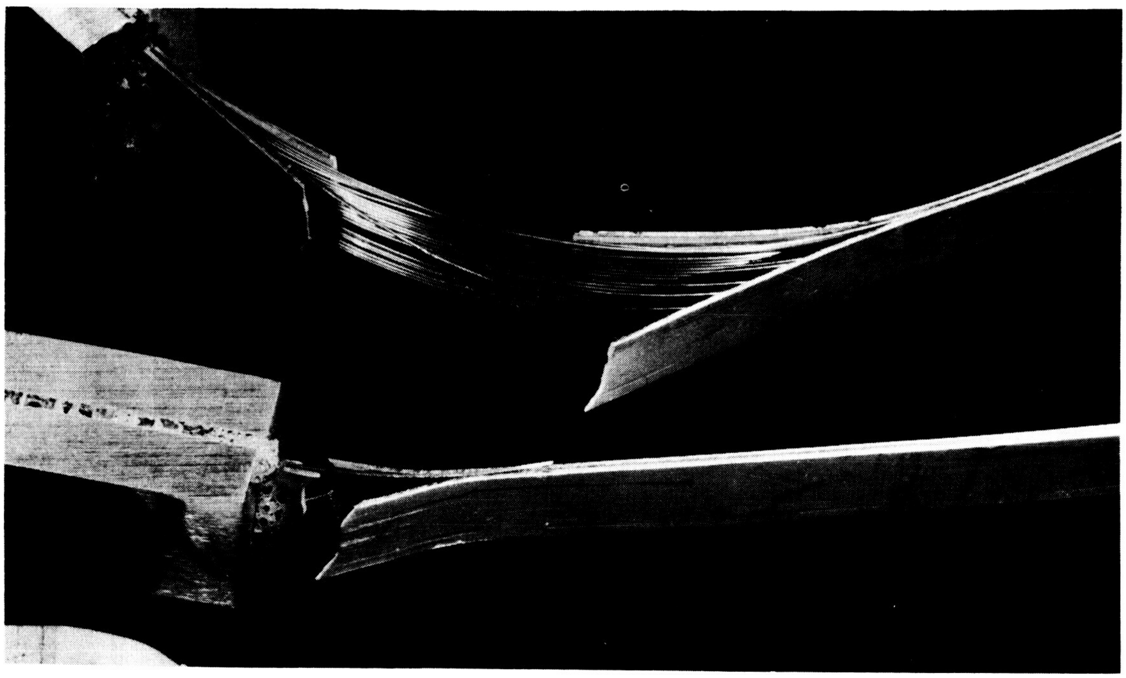


Configuration
No. 1 (Fig.13)
91.0 ksi

FIGURE 31 ALUMINUM + WIRE TENSION SPECIMENS

Wire Diameter .015 inch
Adhesive Sheet Thickness .003 inch
Specimen Width 1/2 inch

Test Temperature 212 F



Test Temperature R.T.

FIGURE 32 ALUMINUM + WIRE COMPOSITE TENSION SPECIMENS
ADHESIVE BOND FAILURE

Configuration No. 3
Faces: Aluminum + Wire
Ti-6Al-4V (HT)
Core: Aluminum HC + Glass HC
Adhesive: FM-1000
Test Temperature 212 F.
58 psi

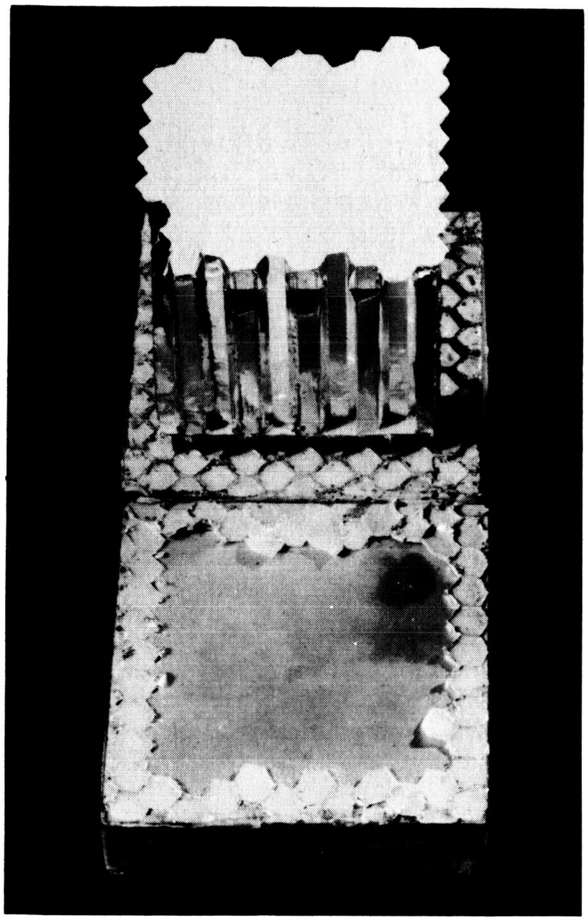


FIGURE 33 FLATWISE TENSION SPECIMEN ADHESIVE BOND FAILURE

Configuration No. 4
Faces: PH15-7 Mo
Core: Aluminum HC
Adhesive: FM-1000
Test Temperature 212 F.
159 psi

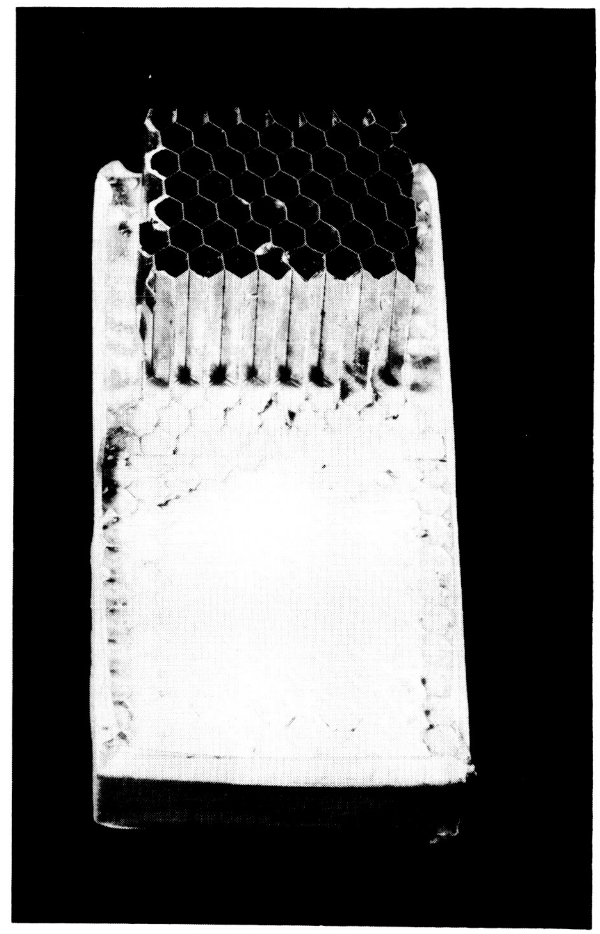


FIGURE 34 FLATWISE TENSION SPECIMEN ADHESIVE BOND FAILURE

Configuration No.1
Faces: Ti-6Al-4V(Ann)
Core: Titanium HC
Adhesive: HT-424
Test Temperature 212 F.
628 psi

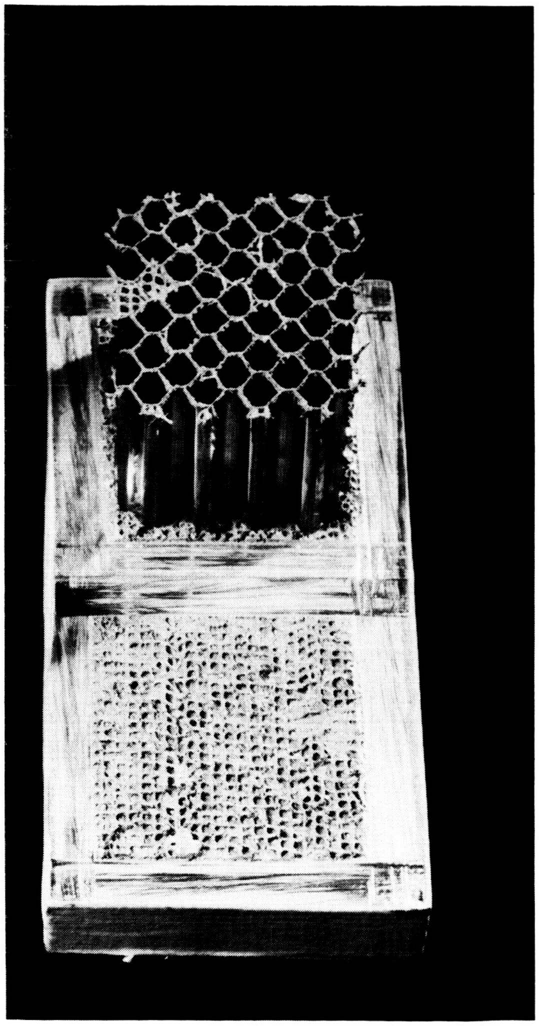


FIGURE 35 FLATWISE TENSION SPECIMEN COHESIVE BOND FAILURE

Configuration No.2
Faces: Glass Fiber
Core: Aluminum HC
Adhesive: HT-424
Test Temperature -109 F.
521 psi

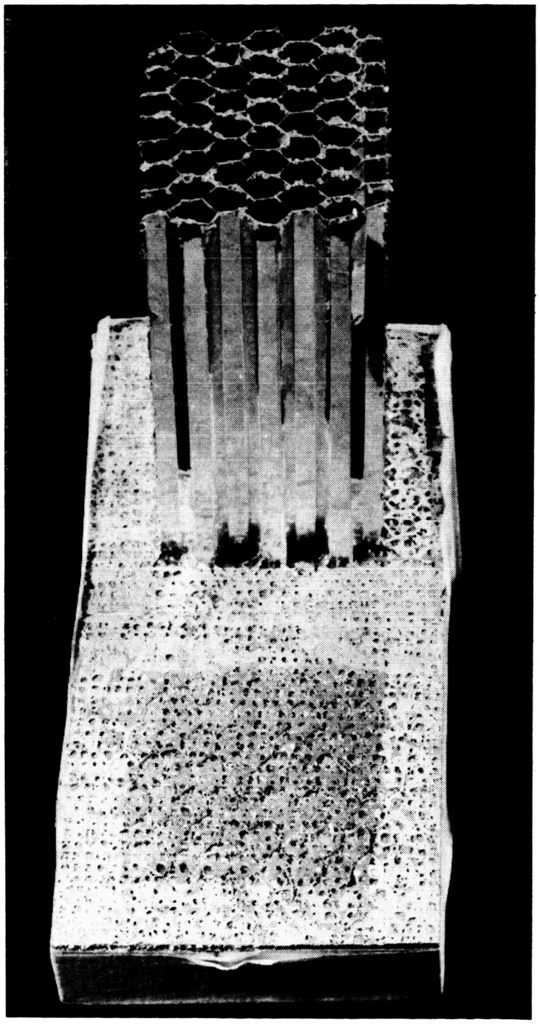


FIGURE 36 FLATWISE TENSION SPECIMEN COHESIVE BOND FAILURE

Configuration No.3
Faces: Ti-6Al-4V(HT)
Aluminum & Wire
Core: Aluminum HC+Glass HC
Adhesive: FM-1000
Test Temperature -109 F.
898 psi

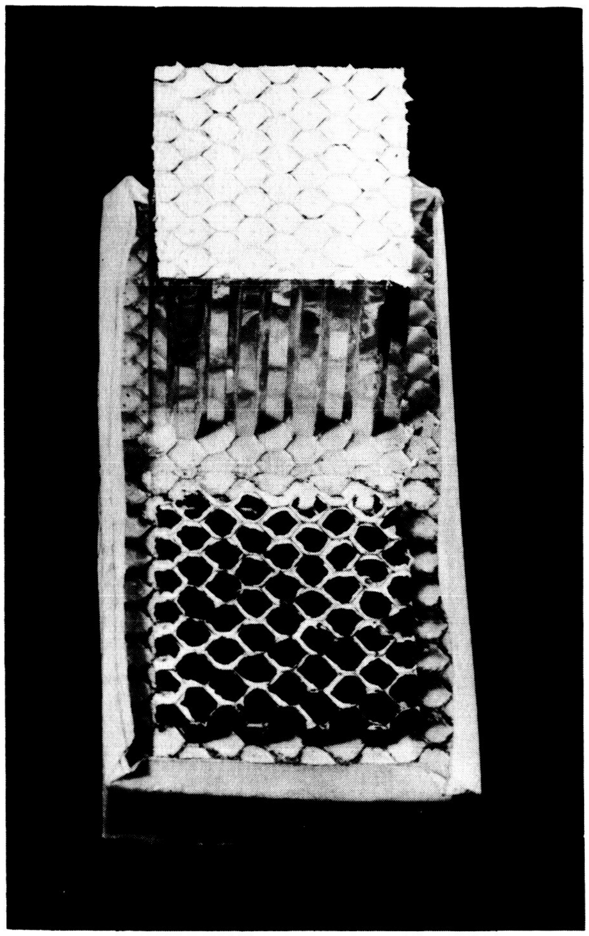


FIGURE 37 FLATWISE TENSION SPECIMEN
COHESIVE BOND FAILURE

Configuration No.4
Faces: PH15-7 Mo
Core: Aluminum HC
Adhesive: FM-1000
Test Temperature -320 F.
1554 psi

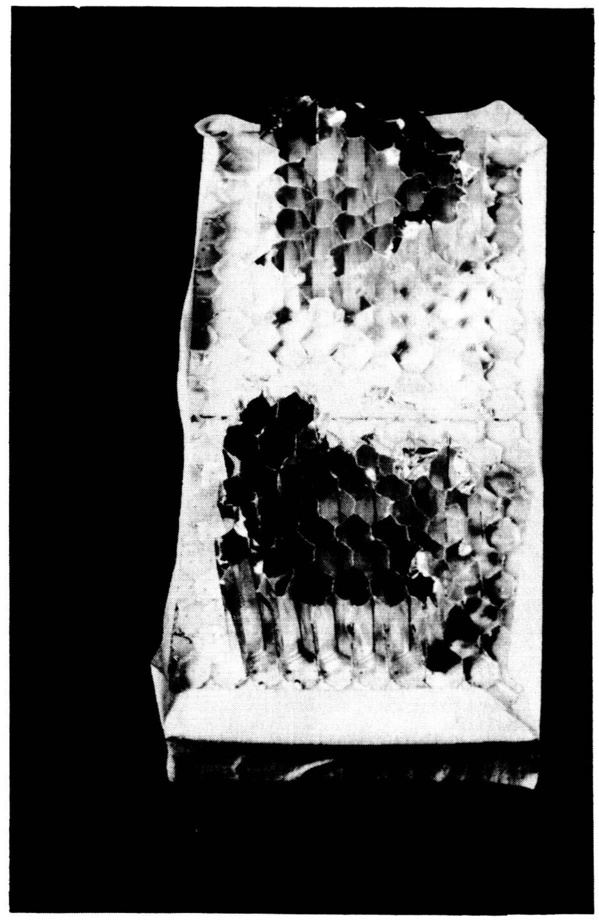


FIGURE 38 FLATWISE TENSION SPECIMEN
CORE FAILURE

and -320 F at PH15-Mo faces, Figure 38, and in aluminum core at room temperature at glass faces, (refer to Table XIV).

The first glass fiber sheets fabricated for the optimum composite specimens exhibited interlaminar failures in the flatwise tension tests (refer to Table XXI). A specimen exhibiting this type of failure is shown in Figure 39.

EDGEWISE COMPRESSION TESTS

Edgewise compression failure in glass fiber sandwich faces occurred through either compression failure or interlaminar failure at all temperatures. Figures 40 and 41 show characteristic glass fiber compression failure in which the glass fibers break sharply and the broken ends tend to slide past each other. When the glass faces are stabilized by low density cores, such as the 4.4 pcf core used in the Optimum Composites, compression failure is generally associated with the core crushing and core shear seen in the above figures. However, initiation of face sheet failure is evidently not dependent upon prior core failure. When 20 pcf core was used, as in the early tests on glass fiber sheets, glass sheet failure occurred without accompanying core failure, Figure 42.

Interlaminar failure in a glass fiber facing is shown in Figure 43. Typically, the face splits in one or more planes parallel to the sheet surface, part of the sheet generally adhering to the sandwich core. This type of failure is considered to result from some face sheet defect, such as a local low resin content, and usually produces low or scattered strength values.

Edgewise compression failure in aluminum + wire laminate facing sheets occurred as either local buckling of the entire sheet, Figure 44, or parting

Configuration No.2
Faces: Glass Fiber
Core: Aluminum HC
Adhesive: FM-1000
Test Temperature R.T.
420 psi

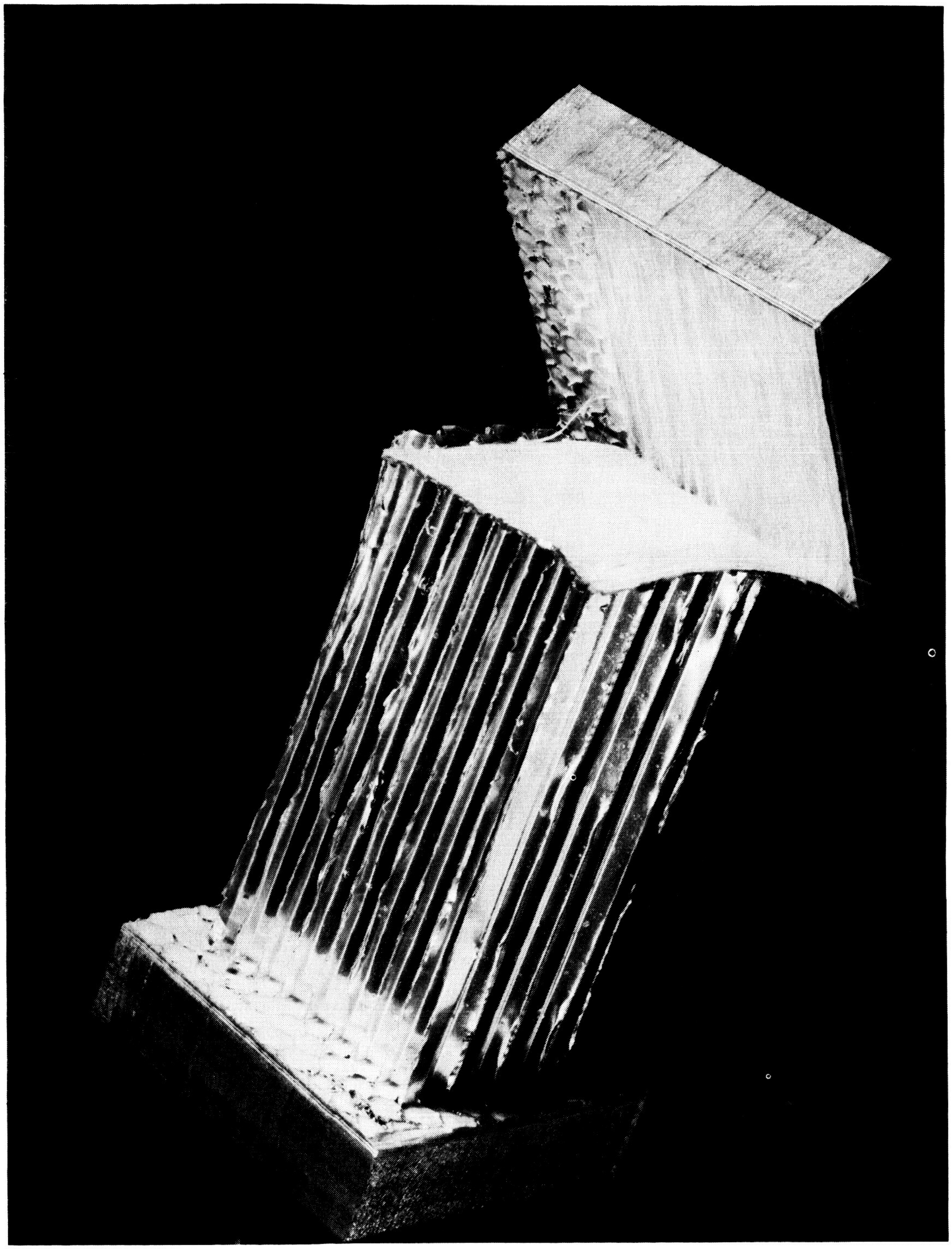
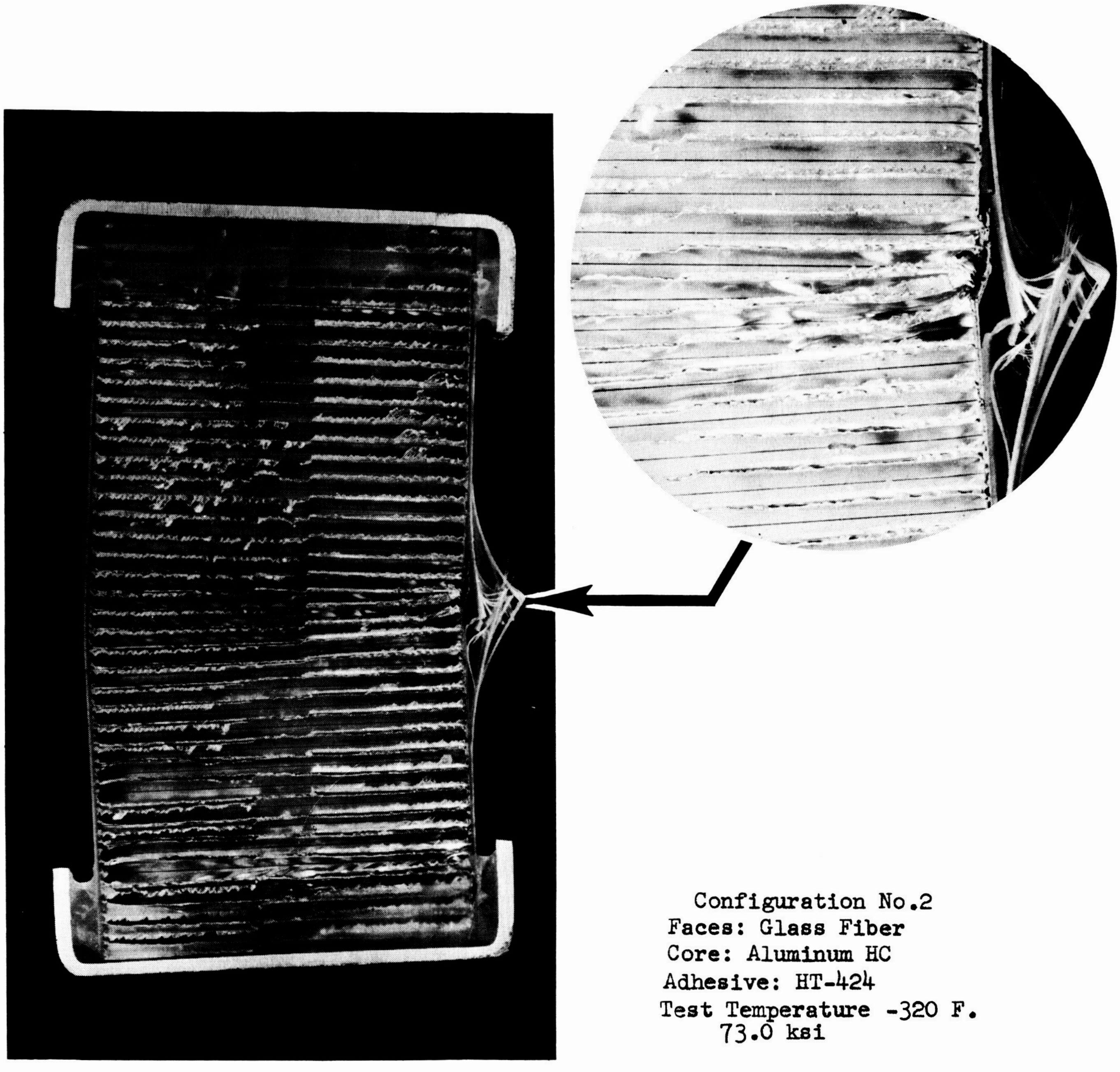


FIGURE 39 FLATWISE TENSION SPECIMEN
GLASS FIBER SHEET FAILURE



Configuration No.2
Faces: Glass Fiber
Core: Aluminum HC
Adhesive: HT-424
Test Temperature -320 F.
73.0 ksi

FIGURE 40 EDGEWISE COMPRESSION SPECIMEN
GLASS FIBER COMPRESSION FAILURE

Configuration No.2
Faces: Glass Fiber
Core: Aluminum HC
Adhesive: HT-424
Test Temperature -320 F.
79.7 ksi

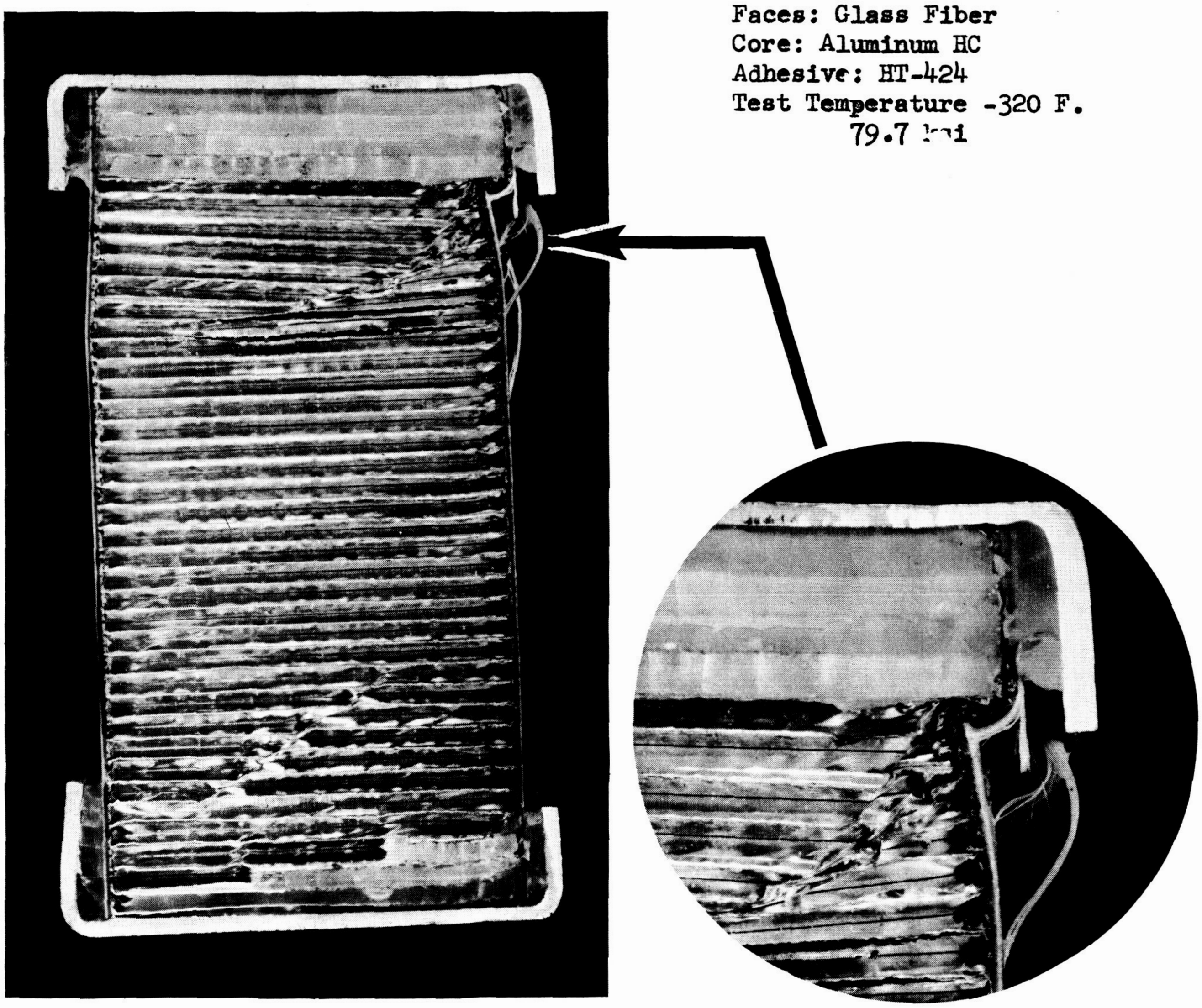


FIGURE 41 EDGEWISE COMPRESSION SPECIMEN
GLASS FIBER COMPRESSION FAILURE

Sheet No. 11
Test Temperature R.T.
49.9 ksi

Sheet No. 6
Test Temperature R.T.
62.1 ksi

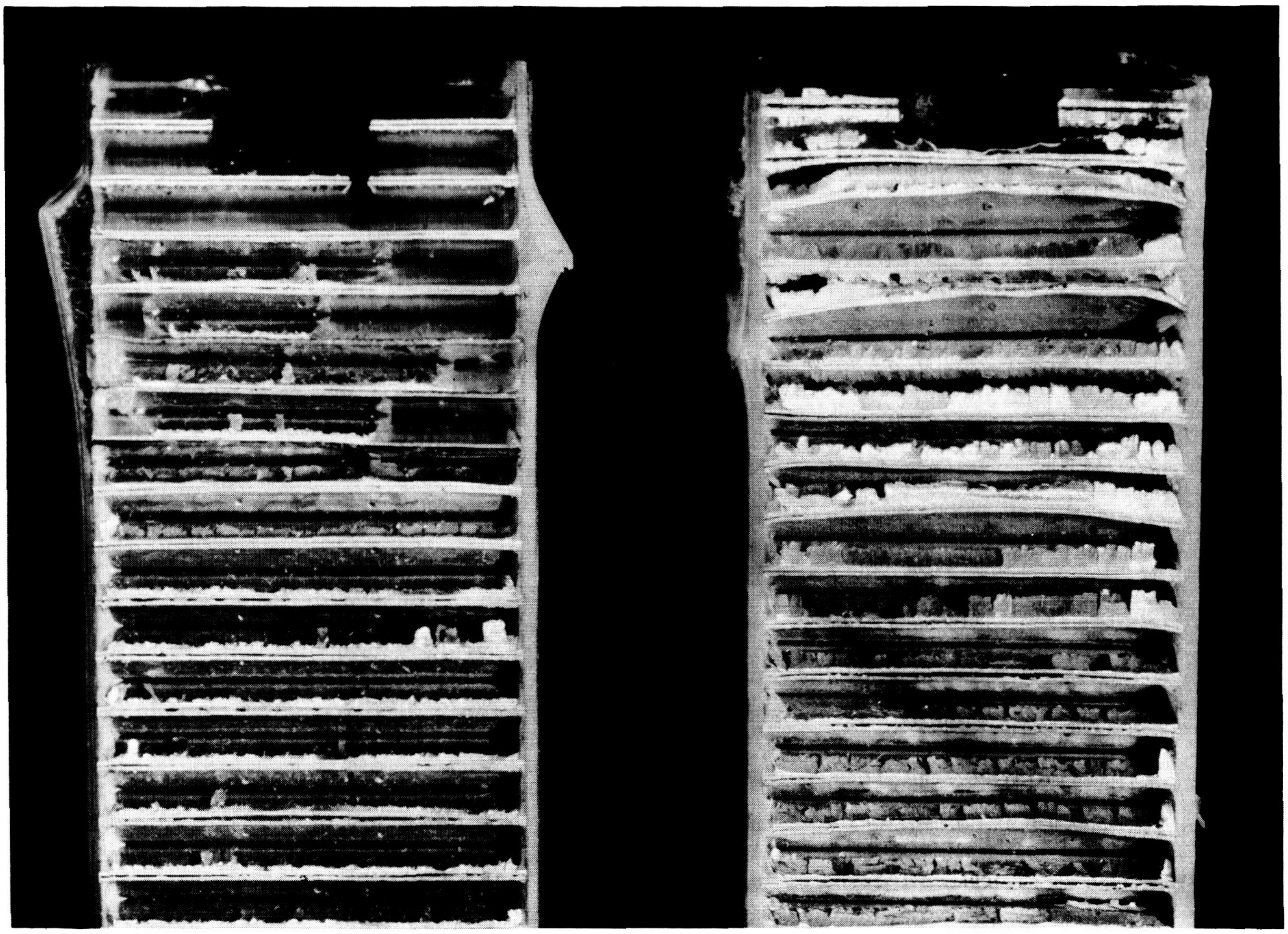
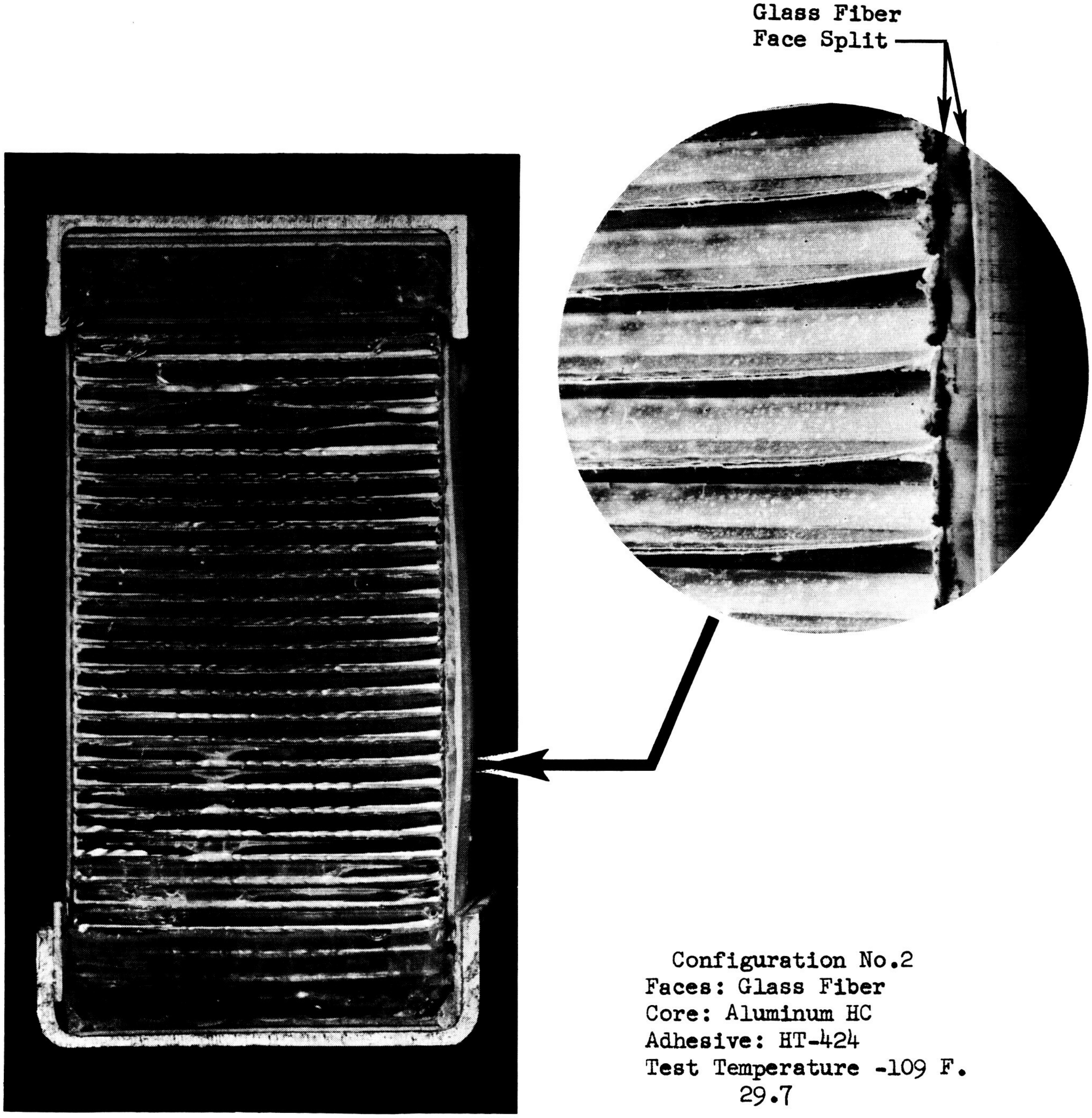
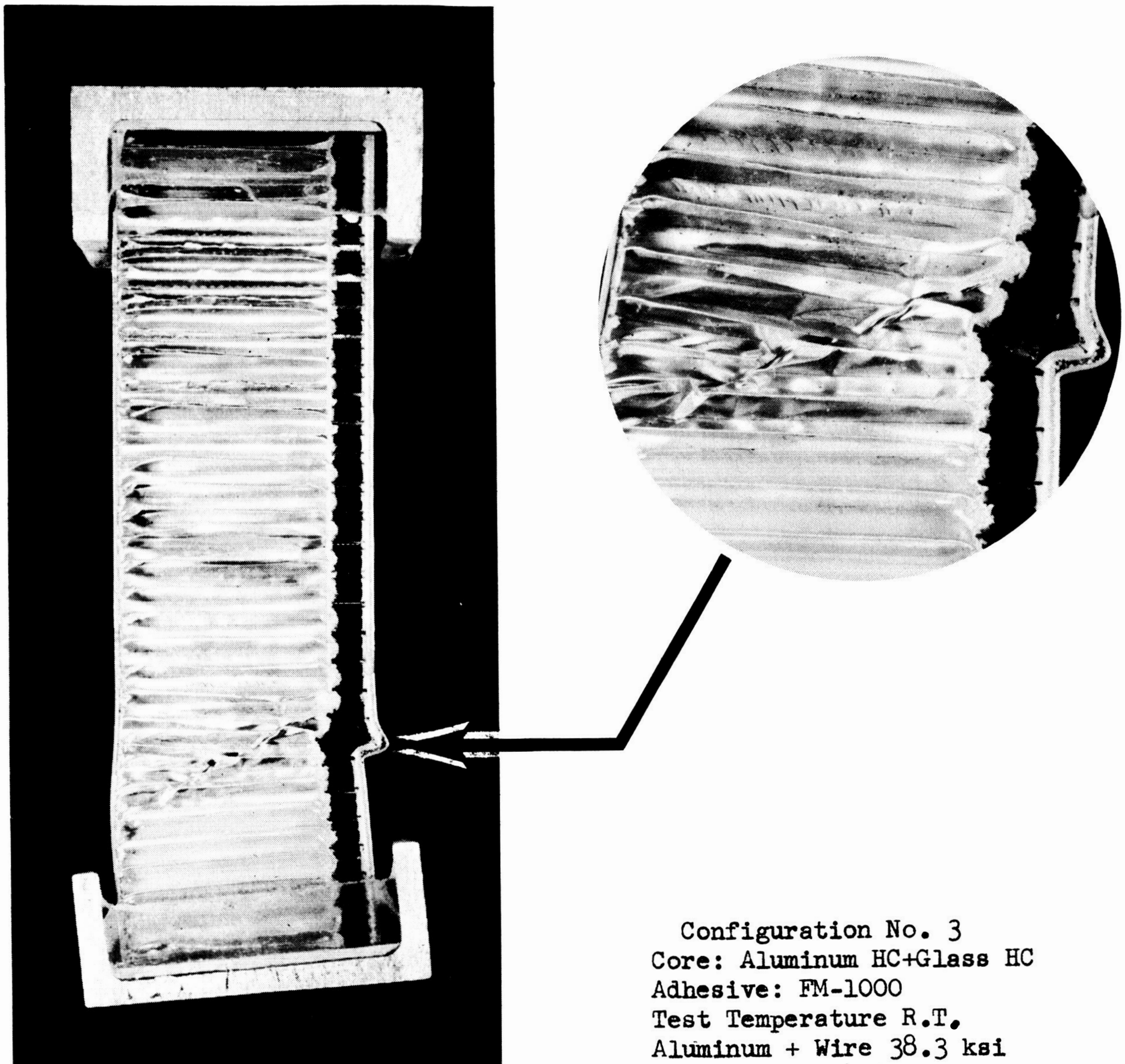


FIGURE 42 EDGEWISE COMPRESSION SPECIMEN
GLASS FIBER COMPRESSION FAILURE



Configuration No.2
Faces: Glass Fiber
Core: Aluminum HC
Adhesive: HT-424
Test Temperature -109 F.
29.7

FIGURE 43 EDGEWISE COMPRESSION SPECIMEN
GLASS FIBER INTERLAMINAR FAILURE



Configuration No. 3
Core: Aluminum HC+Glass HC
Adhesive: FM-1000
Test Temperature R.T.
Aluminum + Wire 38.3 ksi
Titanium 134.2 ksi

FIGURE 44 EDGEWISE COMPRESSION TEST
ALUMINUM + WIRE BUCKLING

of the adhesive bond between the aluminum and the wires, Figure 45, or parting of the bond between the entire sheet and the sandwich core, Figure 46. The latter two types often occurred together. It should be noted that all aluminum to wire bonds and all aluminum + wire face sheet to core bonds were made with FM-1000 adhesive.

Edgewise compression failure in the PH14-7Mo faces of Optimum Composite No. 4 occurred as a local face sheet buckling accompanied either by core crushing and core tension failure, Figure 47, or by FM-1000 adhesive bond failure at the steel face, Figure 48.

Edgewise compression failure in the Ti-6Al-4V faces of Optimum Composite No. 1 occurred at all temperatures as a local face sheet buckling accompanied by cohesive failure in the HT-424 bond, Figure 49. The HT-424 can be seen in this figure adhering to both the face sheet and core.

Configuration: No.3
Core: Aluminum HC+Glass HC
Adhesive: FM-1000
Test Temperature -320F
Aluminum + Wire 37.7 ksi
Titanium 132.2 ksi

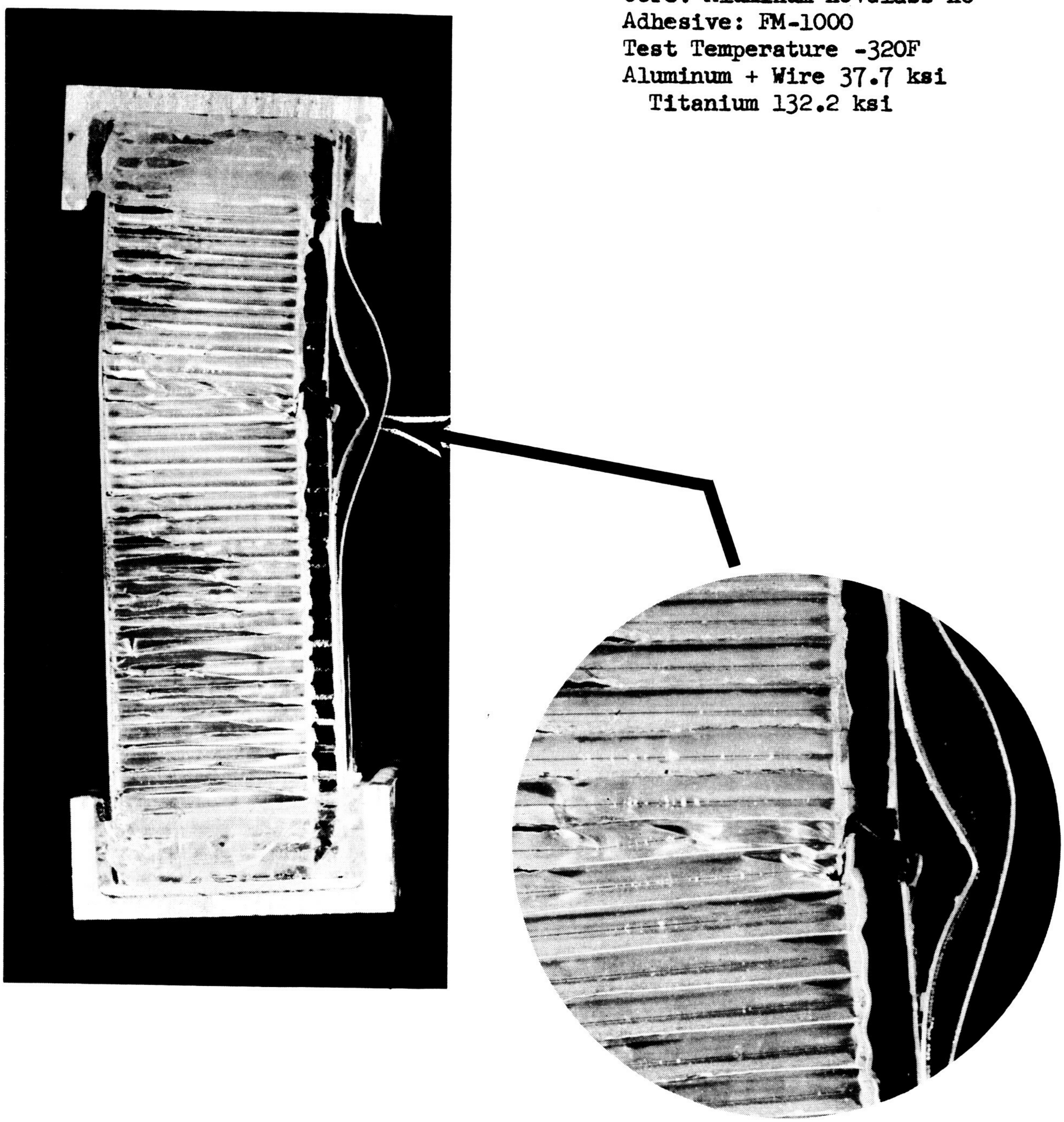


FIGURE 45 EDGEWISE COMPRESSION SPECIMEN
LAMINATE FACE BOND FAILURE

Configuration No.3
Core: Aluminum HC+Glass HC
Adhesive: FM-1000
Test Temperature -320 F
Aluminum + Wire 43.0 ksi
Titanium 150.6

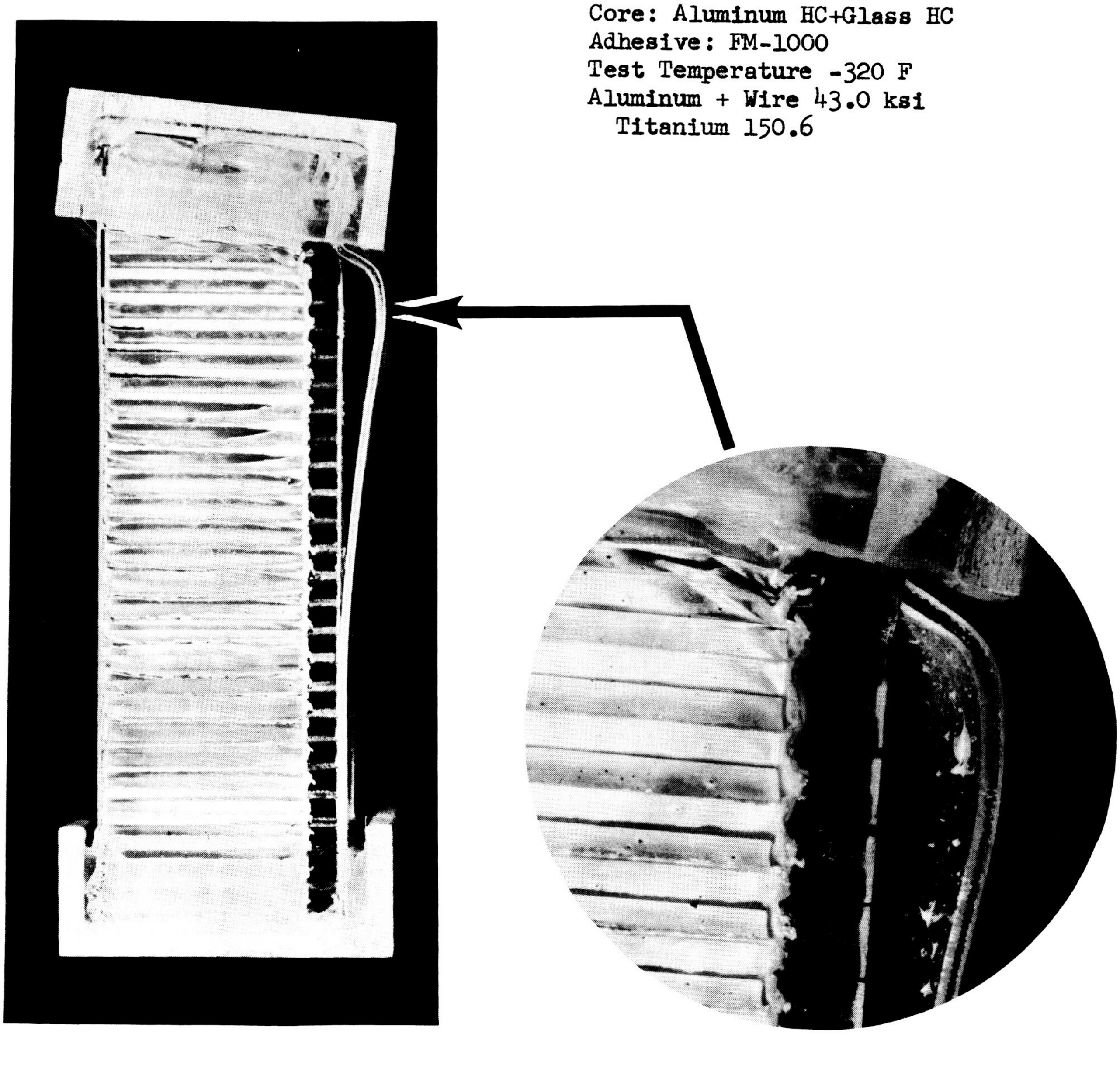


FIGURE 46 EDGEWISE COMPRESSION SPECIMEN
ALUMINUM FACE BOND FAILURE

Configuration No.4
Faces: PH15-7 Mo
Core: Aluminum HC
Adhesive: FM-1000
Test Temperature R.T.
195.1 ksi

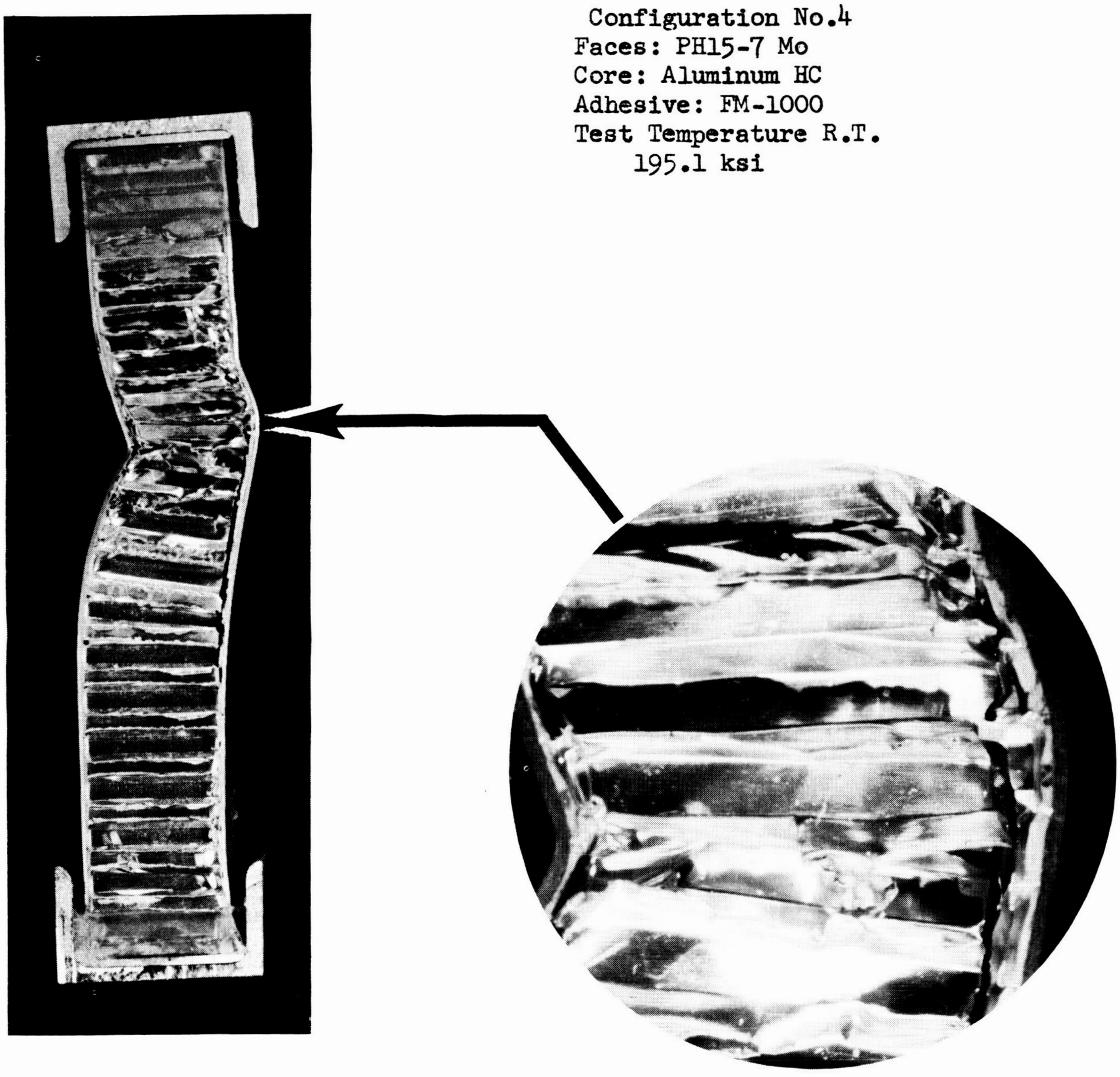
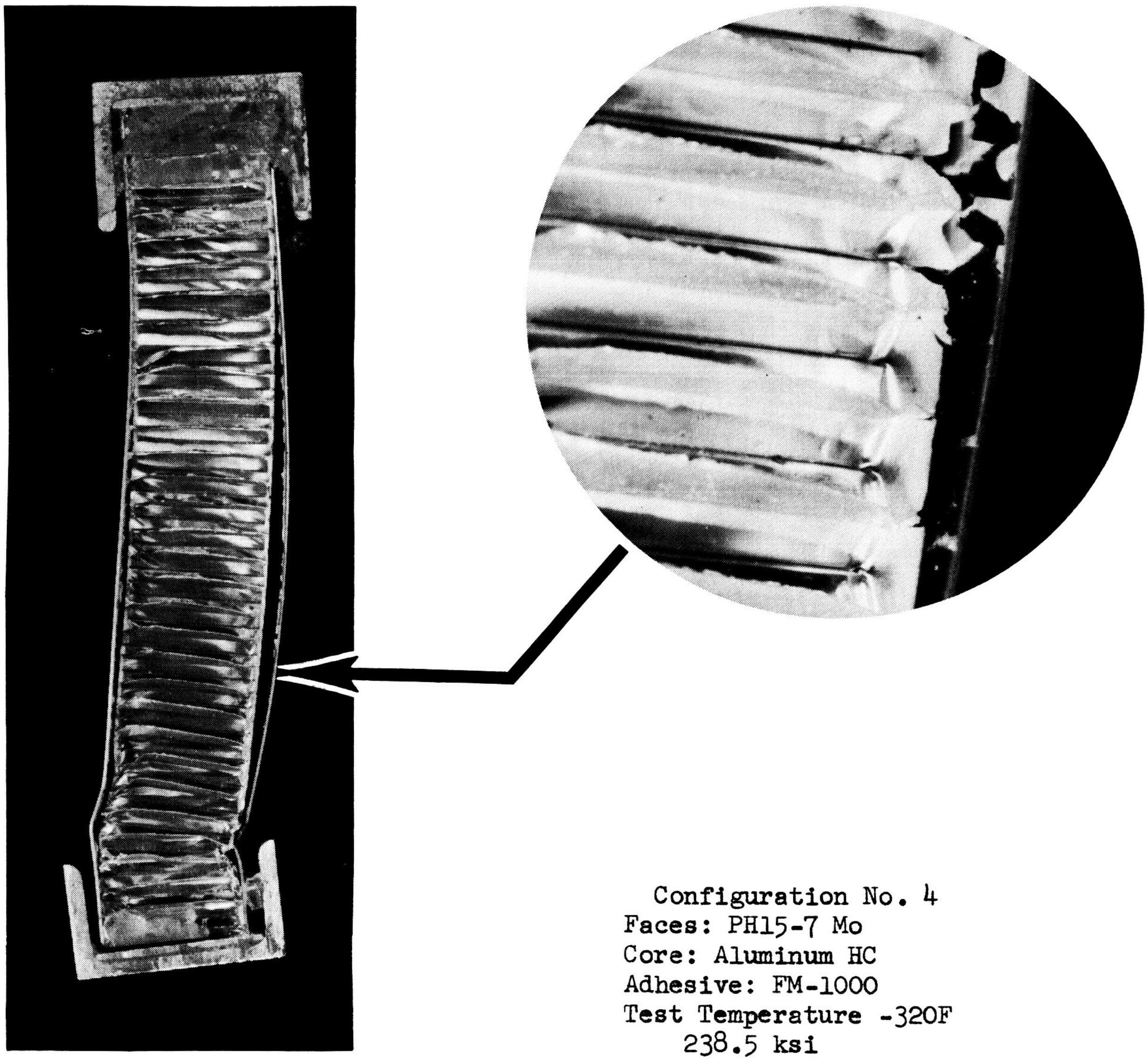
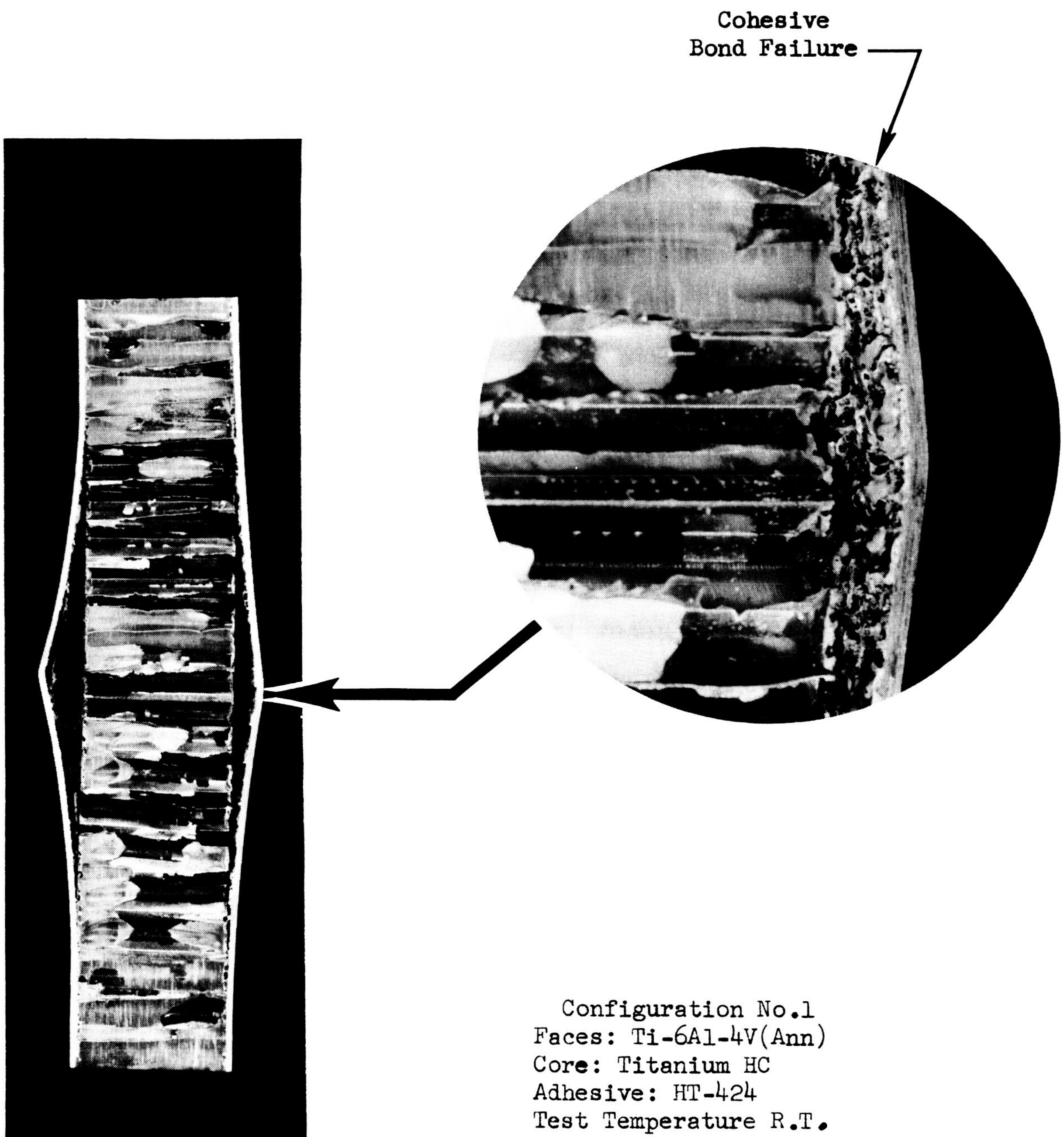


FIGURE 47 EDGEWISE COMPRESSION SPECIMEN
PH15-7 MO LOCAL BUCKLING



Configuration No. 4
Faces: PH15-7 Mo
Core: Aluminum HC
Adhesive: FM-1000
Test Temperature -320F
238.5 ksi

FIGURE 48 EDGEWISE COMPRESSION SPECIMEN
PH15-7 MO FACE BOND FAILURE



Configuration No.1
Faces: Ti-6Al-4V(Ann)
Core: Titanium HC
Adhesive: HT-424
Test Temperature R.T.
127.5 ksi

FIGURE 49 EDGEWISE COMPRESSION SPECIMEN
TITANIUM LOCAL BUCKLING

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APPENDIX A

LOCAL STABILITY

To preclude local failure of the honeycomb facing sheets, stabilization of the cylinder walls requires sufficiently stiff core to overcome three forms of instability, (Reference I). :

1. Intracell buckling
2. Face sheet wrinkling
3. Shear crimping

Intracell buckling failure results when the facing sheets buckle as a panel between the supporting cell walls. This type of failure is typical of thin facing sheets. The following empirical equation is used to evaluate intra-cell buckling:

$$\frac{F_{ci}}{\eta_1} = 0.75\, E_f \left(\frac{t_f}{s}\right)^{3/2}$$

where

$$\eta_1 = \frac{2E_t}{E_f + E_t} \qquad \text{(Plasticity Correction)}$$

E_f = Young's modulus of the face sheet

E_t = Tangent modulus of the face sheet

t_f = Facing sheet thickness

s = Cell size

It is noted that the intracell buckling stress is principally a function of face thickness and cell size. Core density and core depth do not directly affect the intracell buckling allowable stress.

Wrinkling failure of the honeycomb sandwich occurs when the stiffness of the supporting core is insufficient to support the facing sheet at the required stress level. The following empirical equation is used to evaluate wrinkling requirements:

$$\frac{F_{cw}}{\eta_2} = 0.43\sqrt[3]{E_f\, E_c'\, G_c'}$$

where

$$\eta_2 = \sqrt[3]{\frac{3E_t + E_s}{4E_f}} \qquad \text{(Plasticity Correction)}$$

E_f = Young's modulus of face sheet

E_t = Tangent modulus of face sheet

E_s = Secant modulus of face sheet

E_c' = Core compression modulus

G_c' = Core shear modulus

Shear crimping failure is a form of general instability failure where the wave length of the buckle becomes very small due to a low core shear modulus. The failure occurs suddenly and causes the core to fail in shear at the crimp. The following equation is used to calculate the critical shear crimping stress:

$$F_{cs_{MAX}} = \frac{U}{2t_f} = \frac{G'_c\,(c + 2t_f)}{2t_f}$$

where

G'_c = Core shear modulus

c = Core depth

t_f = Face thickness

The plasticity correction factors η_1 and η_2 were equal to one for the 3000 lb/in. compression axial load and 10,000 lb/in. tensile hoop load conditions that were checked.

Core properties E'_c and G'_c were obtained from the following equations:

$$E'_c = 2.13\,(\rho'_c/\rho_c)^{1.415}\,E_c$$

$$G'_c = 2.43\,(\rho'_c/\rho_c)^{1.54}\,G_c$$

where

E_c = Young's modulus of core material

E'_c = Young's modulus of core

G_c = Shear modulus of core material

G'_c = Shear modulus of core

ρ_c = Density of core material

ρ'_c = Density of core

Facing sheet material properties were obtained from Table II in the body of the report. The tangent and shear moduli of the metals were taken from Reference B-2. For the glass, the tangent modulus was assumed equal to the Young's modulus and the shear modulus was assumed equal to 0.4 x Young's modulus.

The intracell buckling and wrinkling equations were developed for isotropic facing sheets and, therefore, application of these empirical equations to orthotropic filament wound glass honeycomb configurations is clearly beyond their intended scope. It was necessary to assume effective properties, thicknesses, and stresses in order to attain the tabulated values.

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INTERNATIONAL AIRPORT
LOS ANGELES 9. CALIFORNIA

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2. Material Properties Handbook, North American Aviation, Inc./Los Angeles Division, Los Angeles 9, California, 15 October 1963

APPENDIX B

THERMAL STRESS EQUATIONS

The following general equations were used to calculate stresses in the faces of sandwiches:

$$\sigma_o = (-\Delta T_o \alpha_o + \Delta T_i \alpha_i) \frac{E_i E_o t_i}{E_o t_o + E_i t_i}$$

$$\sigma_i = (\Delta T_o \alpha_o - \Delta T_i \alpha_i) \frac{E_i E_o t_o}{E_o t_o + E_i t_i}$$

Where

σ_o and σ_i = Thermal stress in the outer and inner faces, respectively, resulting from the temperature changes

ΔT_o and ΔT_i = Temperature change in outer and inner faces, respectively

α_o and α_i = Coefficient of thermal expansion of outer and inner face materials respectively

E_o and E_i = Modulus of elasticity of outer and inner face materials, respectively

t_o and t_i = Thickness of outer and inner faces, respectively

The above equations reduce to the following when the outer and inner faces are of the same material composition:

$$\sigma_o = (-\Delta T_o + \Delta T_i)(\alpha E)\left(\frac{t_i}{t_i + t_o}\right)$$

$$\sigma_i = (\Delta T_o - \Delta T_i)(\alpha E)\left(\frac{t_o}{t_i + t_o}\right)$$

APPENDIX C

FABRICATION METHODS

FILAMENTARY COMPOSITE SHEETS

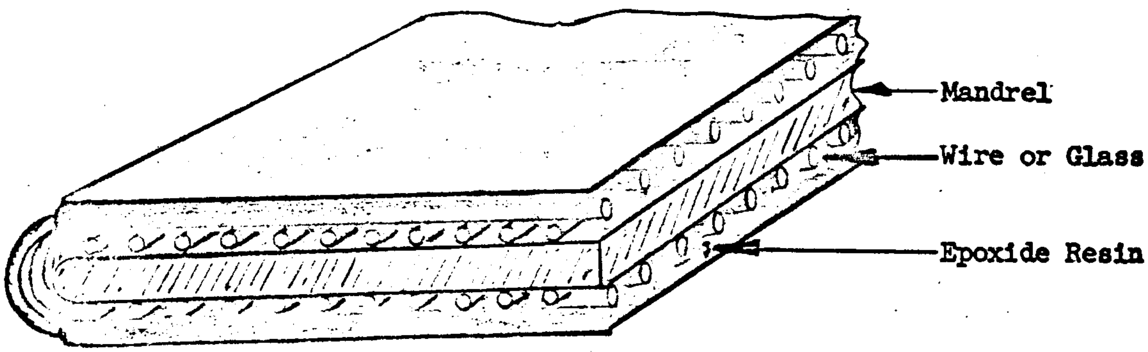
All composite sheets with glass fibers and/or wire in a resin matrix or wire bonded between aluminum or titanium sheets were wound over a flat (1/2 X 11 X 11 inch) mandrel, as shown diagramatically in Figure 1. After winding and curing, the exposed fibers or wires at the ends of the mandrel were cut, producing two complete, similar composite sheets. Figure 2 shows a lathe that was modified to accomplish the winding. Table I gives details of the winding and processing procedures for the sheet materials evaluated under the PHASE I FABRICATION AND TESTING OF COMPOSITE SHEETS.

PHASE I SCREENING COMPOSITES

Details of the methods used in fabricating the screening composite panels are given in Table II.

PHASE II OPTIMUM COMPOSITES

Details of the methods used in fabricating the optimum composite panels are given in Table III.



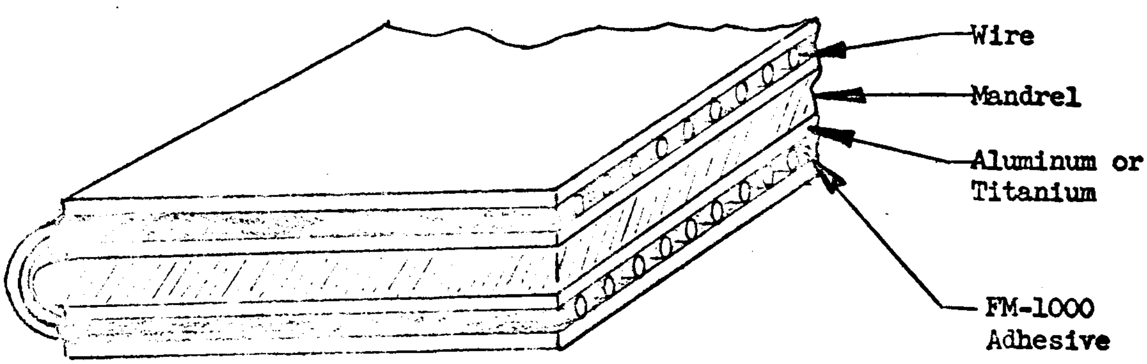


Figure 1 Diagram - Mandrel With Wound Glass Fibers and Wires

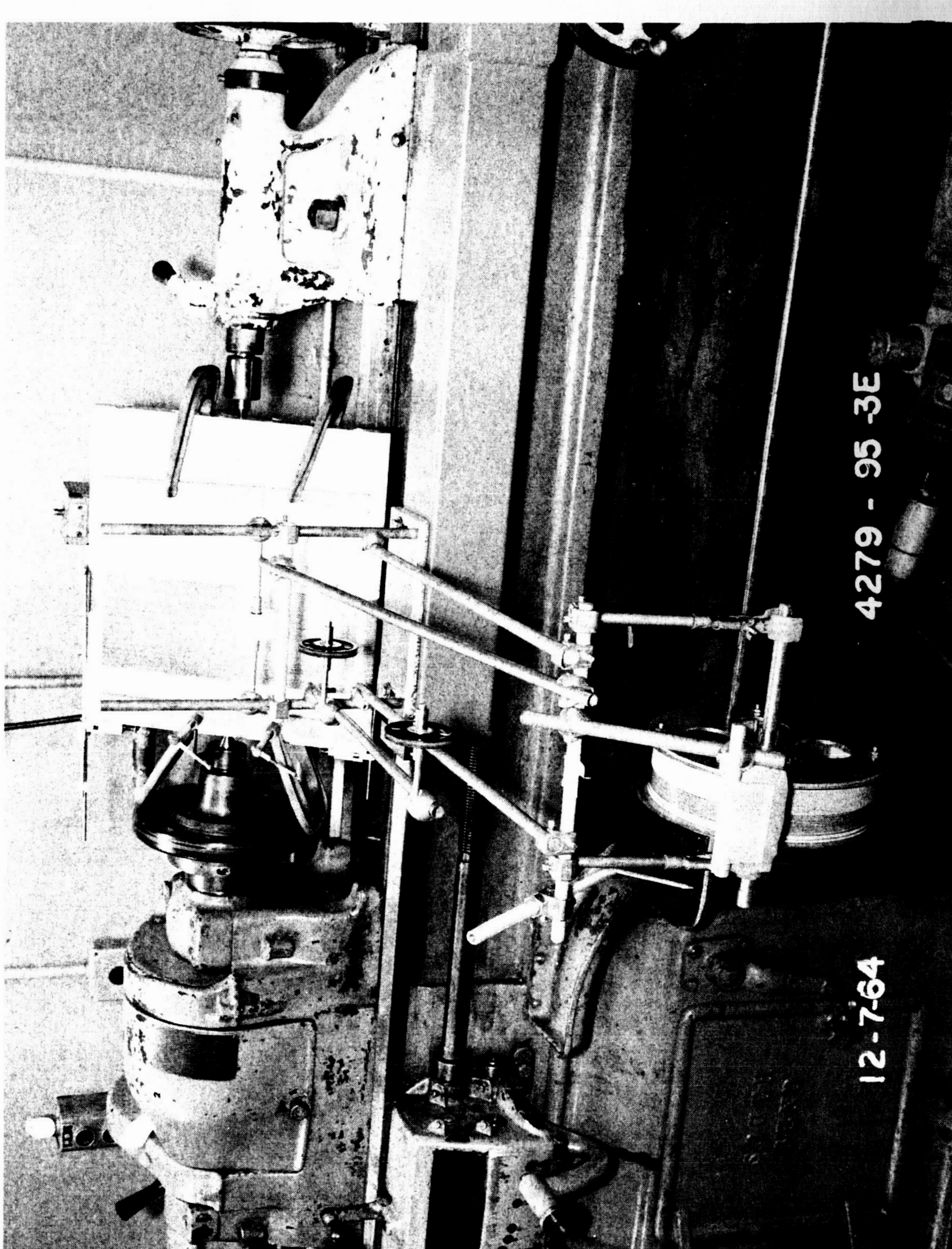
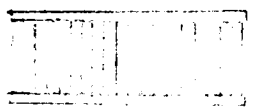
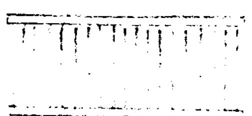
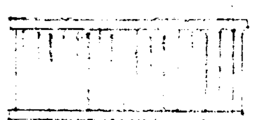
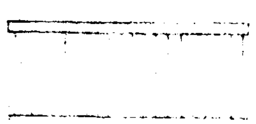


Figure 2 Filament Winding Equipment

COMPOSITE SHEETS	FACE SHEETS	CORE	WINDING PROCEDURE	CLEANING PROCEDURE	SANDWICH BONDING PROCEDURE
Sheet No. 1 Sheet No. 2 **Sheet No. 1 was not made into a sandwich**	Aluminum-Wire Composite **Sheet No. 1** **Thickness = 0.081** **Sheet No. 2** **Thickness = 0.100**	5052-H39 Aluminum H/C 20 lb/ft^3 Thickness = 1.00	Sheet No. 1 Wound Wire:6 plys .004 in dia, bonded between 3 sheets of .016 in. 7075-T6 clad aluminum, Bonded with 8 sheets of .003 in thick FM-1000 adhesive film. Cure:1 1/2 hours at 325° to 345°F-60 psi. Sheet No. 2 same as No. 1 except [illegible] sheets of [illegible] in FM-1000	Wire: Ultrasonic cleaned in Toluene Core: Vapor degrease Aluminum: Hot Sodium dichromate/ Sulfuric acid etch. LA-0110-006	**Face sheets bonded to core with .06 lb/ft^2 FM-1000 Adhesive film.1 1/2 hours at 325° to 345°F -30 psi.**
Sheet No. 3	**Titanium** - Wire Composite Thickness = .070 in.	Same as Sheet No. 2	Same as No. 2 except 3 sheets of .008 in. 6Al-4V Titanium	Wire: Same as No. 2 Core: Same as No. 2 Titanium: Hot Hydrofluoric **acid** -phosphate etch- LA-0110-006	**Same as No. 2.**
Sheet No. 4	Biaxial Filament Glass/Wire Laminate Thickness = .045 in.	Same as Sheet No. 2	Wound Glass: [illegible] plys S-994 Glass Filament 224 Ends/in/ply Wound wire: 2 plys .004 in. Dia Steel Wire - 144 wires/in/ ply Wires Bonded to Glass with 4 **sheets** of .00[illegible] in. thick FM-1000 Adhesive Film Bonded at 325° to 345°F for 1 1/2 hours - 30 psi.	Wire: Same as sheet No. 2. Core: Same as **sheet No. 2.**	**Face sheets bonded to core with .06 lb/ft^2 FM-1000Adhesive Film at 325° to 345°F for 1 1/2 hours - 30 psi.**
Sheet No. 5	Biaxial Filament Wire Laminate	None	Wound Glass: 3 plys S-994 Glass Filament 224 Ends in/ply Wound Wire: 2 plys .004 in. Dia Steel Wire 144 wires/in./ply **Matrix:** Epon 828/NMA/BDMA Resin Resin Content: Cure: 1 1/2 hours at 350°F - 60 psi.	Wire: Same as for Sheet No. 4	**Not made into sandwich because face sheet delaminated after cure.**

COMPOSITE SHEETS	FACE SHEETS	CORE	WINDING PROCEDURE	CLEANING PROCEDURE	SANDWICH BONDING PROCEDURE
Sheet No. 6 	Biaxial Filament (1:1)	Same as sheet No. 4	Wound Glass: 6 plys of S-994 glass filament. 224 ends/in/ply Matrix: Epon 828/NMA/ BDMA Resin. Cure: 1 1/2 hours at 350°F-60 psi Resin Content 16% by Wt.	Core: Same as for Sheet No. 4.	Same as Sheet No. 4.
Sheet No. 7 	Biaxial Filament Glass (1:1) Thickness = .055 inch.	Same as for Sheet No. 2.	Same as for sheet No. 6 except Resin Content 26.7% by wt.	Core: Same as for Sheet No. 2.	Same as for Sheet No. 2.
Sheet No. 8 	Biaxial Filament Glass (2:1) Thickness = No. 8. - .048 in.	Same as for Sheet No. 2	Same as for sheet No. 6. Resin Content: No. 8 - 24.0% by Wt.	Core: Same as for Sheet No. 2.	Sheet No. 8 bonded the same as sheet No. 2.
Sheet No. 9 	Biaxial Filament Glass (2:1) Thickness = .030 in.	Same as for Sheet No. 2.	Wound Glass: 3 plys of S-994 glass filament - 192 ends/in/ply - in one direction and 2 plys 144 ends/in/ply 90° to that. Resin Content 20.1% by wt.	Core: same as for Sheet No. 2.	Same as for Sheet No. 2.

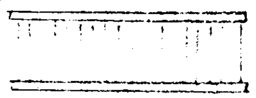
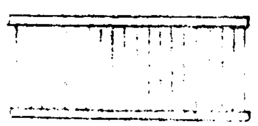
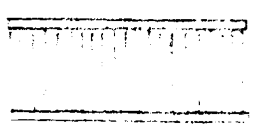
COMPOSITE SHEETS	FACE SHEETS	CORE	WINDING PROCEDURE	CLEANING PROCEDURE	SANDWICH BONDING PROCEDURE
Sheet No. 10 	Biaxial Filament Glass (1:1) Thickness = 0.028 in.	Same as for Sheet No. 2.	Same as for sheet No. 6 except 4 plys of S-994 - 224 ends/in/ply Resin Content: 21.[illegible]% by Wt.	Core: same as for Sheet No. 2.	Same as for Sheet No. 2.
Sheet No. 11	Biaxial Filament Glass (2:1) Thickness = .021 in.	Same as for Sheet No. 2	Same as for Sheet No. 8 except 3 plys of S-994 - 224 ends/in/ply Resin Content = 23.8% by wt.		**Not made into a sandwich.**
Sheet No. 12 	Biaxial Wire (1:1) Thickness = .030 in.	Same as for Sheet No. 2.	8 plys of .004 in dia. Steel Wire - 176 wires/in/ply Bonded with 7 sheets of .001 in. Thick FM-1044 adhesive film with one sheet of .002 in. in FM-1044 Bonded to each face of the com- posite (Total = 2) Cure: 1 1/2 hours at 325° to 345°F - 60 psi.	Wire: Same as for Sheet No. 2. Cure: Same as for Sheet No. 2.	Same as for Sheet No. 2.
Sheet No. 13 	Biaxial Wire (2:1) Thickness = .022	Same as for Sheet No. 2.	Same as for Sheet No. 12 except 6 plys - 176 wires/in/ply, 5 sheets of .001 in. FM-1044 and 2 sheets of .002 in. FM-1044	Wire: Same as for Sheet No. 2. Core: Same as for Sheet No. 2.	Same as for Sheet No. 2.

TABLE II
FABRICATION PROCESS FOR SCREENING COMPOSITES

SCREENING COMPOSITE CONFIGURATION	FACE SHEETS	CORE	WINDING PROCEDURE	CLEANING PROCEDURE	SANDWICH BONDING PROCEDURE
LN_2- I	6Al-4V Titanium Condition A Thickness = .0[illegible]0 Inches.	Titanium - 7[illegible] H/C, 3.[illegible] lbs/ft^3 Thickness = 1.06 Inches	NONE	Titanium: NAA/LAD Process Specification LA0110-006: Alkaline cleaning and an inhibited hot hydro-fluoric acid pickel and phosphate etch Core: vapor degrease	Bonded with FM-1000 (.06 lb/ft^2 Adhesive film at 20 psi, 325° to 395°F for 90 mins.
LN_2- II	Aluminum - Wire Composite Thickness = .0[illegible]5 Inches	Aluminum 50 2-H39 H/C 4.4 lbs/ft^3 Thickness= 1.9[illegible] Inches	Filament wound (.004 in. dia) steel wires 4 plys at 192 wires/inch/ply bonded between 3 sheets of .010 inch 2014-T6 Aluminum with [illegible] sheets of .001 Inch FM 1044 Adhesive film.	Wire: Ultrasonic cleaned in Toluene Core: Vapor Degrease Aluminum Sheets: NAA/LAD Process Specification LA0110-006 (Hot sulfuric dichromatic - sulfuric acid)	Same as LN_2- I
LN_2- III	Biaxial Filament glass tape and wire laminate Thickness = .050	Same as LN_2- II Thickness = 2.33 inches.	Wound .010 in. dia steel music wire 2 plys - [illegible]5 ends/in/ply between 6 plys of pre-impregnated unidirectional [illegible]-[illegible]4 glass filament tape 130 ends/in/ply and 2 plys of .00[illegible] inch and 2 plys of .002 in. thick FM-1044 Adhesive Film.	Wire: Same as LN_2- II Core: Same as LN_2- II	Same as LN_2- I
LOX-I (a)- (b)-	(a) 6Al-V Titanium (HT) Thickness= .034 inch. (b) Aluminum-Wire Composite Thickness=.045 Inch.	Same as LN_2- II Thickness= 1.70 Inch.	Aluminum - Wire: Same as LN_2- II	Wire: Same as LN_2- II Aluminum: Same as LN_2- II Core: Same as LN_2- II Titanium: Same as LN_2-I	Same as LN_2- I
LOX - II	Biaxial Filament Glass Tape (2:1) Thickness= .050 Inch.	Same as LN_2- II Thickness = 3.00 Inch	Unidirectional-preimpregnated S-994 glass tape - 12 plys 130 ends/inch/ply	Core: Same as LN_2- II	Same as LN_2- I

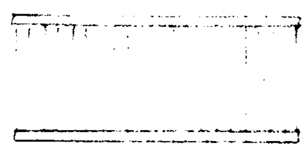
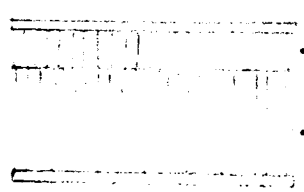
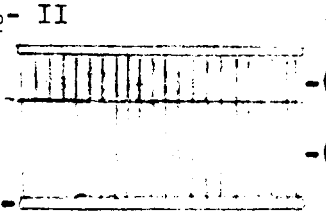
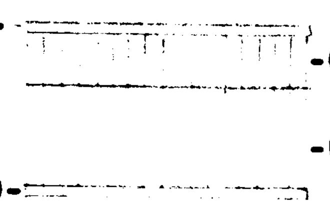
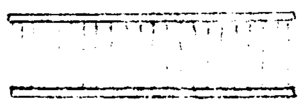
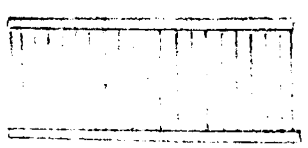
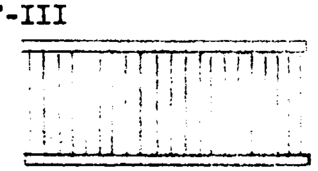
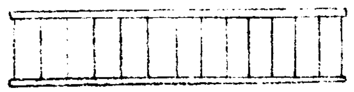
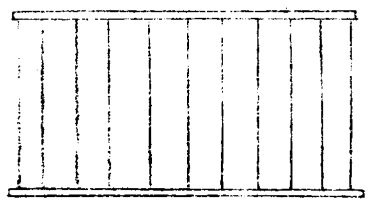
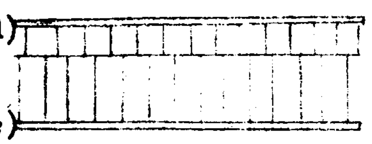
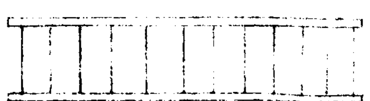
SCREENING COMPOSITE CONFIGURATION	FACE SHEETS	CORE	WINDING PROCEDURE	CLEANING PROCEDURE	SANDWICH BONDING PROCEDURE
LOX III 	Biaxial Filament wound glass (2:1) Thickness = .050 Inches.	Same as LN_2- II (See Table II) Thickness = [illegible].00 Inches.	Same as face sheets for Optimum Composite Configuration No. 2 (See Table III) except cure pressure was [illegible] psi and resin content 20% by wt.	Face sheets - sanded and wiped with MEK Core: Same as LN_2- II	Same as LN_2- I (See Table II)
LH_2 - I (a) - (b) - -(d) -(e) (c)- 	(a) Biaxial Filament Wound glass (2:1) Thickness= .035 in. (b) 3003 Aluminum foil thickness= 0.003 inch. (c) 6Al-4V Titanium (Ann) Thickness = .065 Inch.	(d) HRP Glass H/C 8 lbs/ft^3 Thickness= .25 in. (e) Aluminum 5052 5052-H39 H/C 4.4 lbs/ft^3 Thickness=1.[illegible]8 in.	Wound Glass: Same as LOX III except. 6 plys - 1[illegible] ends/in/ply Resin content 20% by wt.	Wound Glass: Same as LOX III Core: Same as LN_2- II Titanium: Same as LN_2- I Aluminum Foil: Same as LN_2- II	Same as LN_2- I
LH_2- II (a)- (b)- -(d) -(e) (c)- 	(a) 6Al-4V Titanium (HT) Thickness = .042 In. (b) 3003 Aluminum Foil Thickness=.003 inch. (c) 6Al-4V Titanium (Ann) Thickness=.042 inch.	(d) Same as LH_2-I (e) Aluminum 5052-H39 H/C 3.0 lbs/ft^3 Thickness=0.99 in.	NONE	Titanium: Same as LN_2- I Aluminum Foil: Same as LN_2- II Core: Same as LN_2- II	Same as LN_2- I
LH_2- III (a)- -(d) (b) -(e) (c)- 	(a) Biaxial Filament Wound glass (2:1) Thickness-.055 in. (b) 3003 Aluminum Foil Thickness = .003 inch. (c) Aluminum-Wire Composite Thickness = .045 in.	(d) Same as LH_2-I (e) Same as LH_2-I Thickness=2.63 in.	Wound Glass: Same as LOX III except 9 plys [illegible] ends/in. ply and Resin Content 20%/wt. Wire-Aluminum: Same as LN_2- II	Wound Glass: Same as LOX III Aluminum Foil: Same as LN_2- II Core: Same as LN_2- II	Same as LN_2- I

TABLE II - CONTINUED
FABRICATION PROCESS FOR SCREENING
COMPOSITES

SCREENING COMPOSITE CONFIGURATION	FACE SHEETS	CORE	WINDING PROCEDURE	CLEANING PROCEDURE	SANDWICH BONDING PROCEDURE
HF-I 	PH 15-7Mo Steel Thickness = 0.25 Inch	Same as LN_2- II Thickness = 1.03 Inch.	NONE	Steel: Inhibited Fluoride etch Core: Same as LN_2- II	Same as LN_2- I
HF-II (a)- (b)- 	(a) Maraging Steel Thickness - .030 in. (b) Biaxial Filament Wound Glass (2:1) Thickness = .035 in.	Same as LN_2- II Thickness = 2.10 in.	Wound Glass: Same as LOX III except 6 plys 1[illegible] ends/inch/ply Resin Content = 20% by wt.	Steel: Same as HF-I Wound Glass: Same LOX III Core: Same as LN_2- II	Same as LN_2- I
HF-III 	6Al-4V Titanium (HT) Thickness = .032 In.	Same as LN_2- II Thickness = 1.52 in.	NONE	Titanium: Same as LN_2- I	Same as LN_2- I

OPTIMUM COMPOSITE CONFIGURATION	FACE SHEETS	CORE	WINDING PROCEDURE	CLEANING PROCEDURE	SANDWICH BONDING PROCEDURE
NO. 1 	6Al-4V Titanium, Condition A Thickness = .040 inches	Titanium - 75A H/C, 4.4 lbs/ft^3 Thickness = 1.00 inches	NONE	Face Sheets-Immersed for 2 minutes at RT in 841 ml 37-38% HCL, 89 ml 85-87% H_3PO_4, 43 ml 60% HF. Water rinse followed by de-ionized water rinse-Forced air dry. Bond within 5-10 mins. Core-Toluene wash - MEK spray	Bonded with HT424 at 20 psi, 350°F for 75 minutes.
NO. 2 	Biaxially Filament wound glass. Thickness = .057 inches	Aluminum 5052-H39 H/C, 4.4 lbs/ft^3 Thickness = 3.00 inches.	Single end S-994 glass Filaments were wound on a flat mandrel at 224 ends/inch in [illegible] plys and, at 90°, 4 plys were wound at 144 ends/inch. Between plys epoxy resin matrix material (100 pbw Epon 828, 90 pbw NMA, 0.5 pbw BDMA) was applied to the glass. The panels still on the mandrel were press bonded at 40 psi, 350°F, for 1 hr. to obtain 18-20% resin content for Set No. 1. Set No. 2 was the same except 20 psi bonding pressure was used to obtain 23-25% resin content. All panels were post cured 1 Hr at 350°F.	Face Sheets-Sanded and wiped with MEK	Set No. 1 Bonded with F-1000 at 20 psi, 325-345°F, for 1 1/2 hours. Set No. 2 Same as Configuration 1 above.
NO. 3  	(a) Aluminum-Wire Composite Thickness = 0.045 (b) 3003 Aluminum Foil Thickness = 0.003 inch (c) 6Al-4V Titanium Condition STA Thickness = 0.030	(d) HRP Glass H/C 8lbs/Ft^3 Thickness =0.25 (e) Aluminum 5052-H39 H/C 4.4 lbs/Ft^3 Thickness =1.55	Aluminum-Wire Composite-Steel wire (.015 in. dia.) was filament wound at 50 wires/inch and bonded between two sheets of 0.015 inch 2014-To with FM-1000 adhesive	Face Sheets (a) & (b) Sodium dichromate-Sulfuric acid etch. (c) Same as for Configuration No. 1 above. Core (e) - Toluene wash-MEK spray.	Bonded with FM-1000 at 20 psi, 325-345°F, for 1 1/2 Hrs.
NO. 4 	PH15-7Mo Steel Condition RH 1075 Thickness = 0.026	Aluminum 5052-H39 H/C 4.4 lbs/ft^3 Thickness = 1.03		Face Sheets Inhibited Fluoride Acid etch. Core - Toluene wash - MEK spray	Bonded with FM-1000 at 20 psi, 325-345°F, for 1 1/2 Hrs.

APPENDIX D

TEST METHODS

TESTS AT ROOM TEMPERATURE, 212 F, -109 F, and -320 F AT NAA/LAD

GENERAL

In general, testing of sandwich materials was conducted in accordance with the military testing specification of Reference (a). Metallic monolithic sheet materials were prepared and evaluated in accordance with Reference (b). Composite sheet materials, including metals and wire laminates and glass fibers or wires in a resin matrix, were tested in accordance with Reference (c). Core shear tests were conducted in accordance with Reference (d).

Either a Baldwin 120,000 pound Universal Testing Machine or a Riehle 120,000 pound Electro-Mechanical Testing Machine was used for load application.

ELEVATED AND LOW TEMPERATURE TESTING

The methods that were used for maintaining and measuring test temperatures were the same for the facing tension, flatwise tension, flatwise compression, core shear, and edgewise compression tests.

All testing at +212 F was accomplished in the type of hot air furnace shown in Figure 1. Specimen temperature was monitored with chromel-alumel thermocouples.

Testing at -109 F was accomplished by two methods. In one method specimens were immersed directly and allowed to reach thermal equilibrium in a mixture of solid carbon dioxide and trichlorethylene, Figure 2. In the other they were cooled in a gaseous nitrogen chamber in which the temperature was monitored with an iron - constantan thermocouple, Figure 3.

Testing at -320 F was accomplished by direct immersion in liquid nitrogen, Figure 4.

FACING TENSION TESTING

Monolithic metal sheet test coupons and glass fiber or wire in resin coupons were prepared in accordance with drawings TT-11010, and TT-16182, respectively. Various types of coupons were used with the aluminum + wire laminates. These are described in the body of the report in sections presenting test results. The test specimen designs used for composite sheet materials, were adopted after some experimentation. Early composite test specimens were rectangular in shape and had no end reinforcements. Considerable difficulty was experienced with premature failure in these specimens due to uneven applications of load. Use of the end reinforcement pads, provided considerable improvement. However, some premature failures continued to occur, with attendant scatter of data, due to the difficulty of controlling specimen preparation and geometry.

A conventional 2-inch averaging extensometer, Figure 5, was used for all room temperature tension tests on metallic materials. The point contacts on this instrument tended to cause premature failure in the resin matrix specimens. A clamp-on extensometer, Figure 1, with a line contact, was used with all resin matrix specimens. This type of extensometer was used also in all tension tests at temperatures other than room temperature.

EDGEWISE COMPRESSIVE TESTING

Edgewise compression specimens were prepared in accordance with drawing TT-16808. The loading mechanism and mechanical deflectometer for edgewise compression tests at room temperature are shown in Figure 6. The strain gage in this figure was used only in the check out tests discussed below.

A mechanical deflectometer arrangement which was adaptable to confined spaces was used for edgewise compression testing at elevated temperature and cryogenic testing, Figures 7 and 8.

The accuracy of the load deformation system used for the edgewise compression tests was checked out at room temperature by comparing the mechanical averaging deflectometer system with strain gages and an optical strain measuring device (OPTRON) in edgewise compression tests on a brazed PH15-7Mo sandwich. Figure 9 shows the complete mechanical loading and mechanical deflectometer set-up with the strain gages and gage instrumentation, Figure 10 shows the optical strain measuring equipment in position, and Figure 11 show a diagram of the check out system and a plot of the strain readings obtained by the various methods.

The ball through which loading was applied in edgewise compression, Figure 6, was positioned so as to obtain equal deflection in opposite faces, as would occur in axial compressive loading in a tank wall. With like sandwich faces the position of the ball was midway between the two faces. With unlike faces the ball was placed at the "elastic center." The "elastic center" was determined from the areas and the elastic moduli of the two faces:

Thus, if

A_1 = Area of Face No. 1

E_1 = R.T. modulus of Face No. 1

A_2 = Area of face No. 2

E_2 = R.T. modulus of Face No. 2

D = Perpendicular distance between the face centers.

The loading ball would be positioned on the line connecting the center of the faces and at the distance D_1 from Face No. 1

Where $D_1 = \dfrac{A_2 E_2}{A_1 E_1 + A_2 E_2} D$

With unlike sandwich faces the above loading set-up assures equal deflections only at room temperature and only up to the proportional limit of the materials.

The total edgewise compression load, Pt, on the sandwich was proportioned between the two faces as follows:

$$P_2 = \frac{D_1}{D} P_t \text{ and } P_1 = \frac{D-D_1}{D} P_t$$

Where P_1 and P_2 are the loads on Face No. 1 and Face No. 2, respectively, and D and D_1 are as defined above.

Compressive stress for each face was calculated as follows:

$$f_c = \frac{P}{t\ b}$$

Where: fc = face stress

t = face thickness

P = face load

b = sandwich width.

FLATWISE TENSION TESTING

Flatwise tension specimens were prepared in accordance with drawing number TT-14336. The flatwise tension loading fixture that was used at RT, 212 F, - 109 F, and - 320 F is shown in Figure 12.

FLATWISE COMPRESSION TESTING

Flatwise compression specimens were prepared in accordance with drawing number TT-13175. The flatwise compression loading fixture and the deflectometer set-up used for room temperature testing is shown in Figure 13. The same deflectometer was used for both flatwise compression testing and edgewise compression testing at 212 F, -109 F, -320 F and is shown in Figure 7. When used in the flatwise compression tests, this instrument was clamped to the edge of the sandwich faces.

HONEYCOMB CORE SHEAR TESTING

Honeycomb core shear specimens were prepared in accordance with drawing TT-13088. A fixture was used to maintain alignment of the loading plates during the adhesive cure cycle. Figures 14 and 15 show the core shear specimen and the fixture before assembly and after assembly, respectively.

The test loading and deflectometer systems used for core shear testing at RT, 212 F, -109 F, and -320 F is shown in Figure 16. Load was applied in compression. The deflectometer was attached to the loading plates and immediately adjacent to the core, to eliminate recording of loading plate deformation.

Core shear modulus was calculated as follows:

$$G_c = \frac{P}{ab} \times \frac{t_c}{\Delta}$$

Where G_c = core shear modulus

P = Load at deflection Δ

a = Core length

b = Core width

t_c = Core thickness

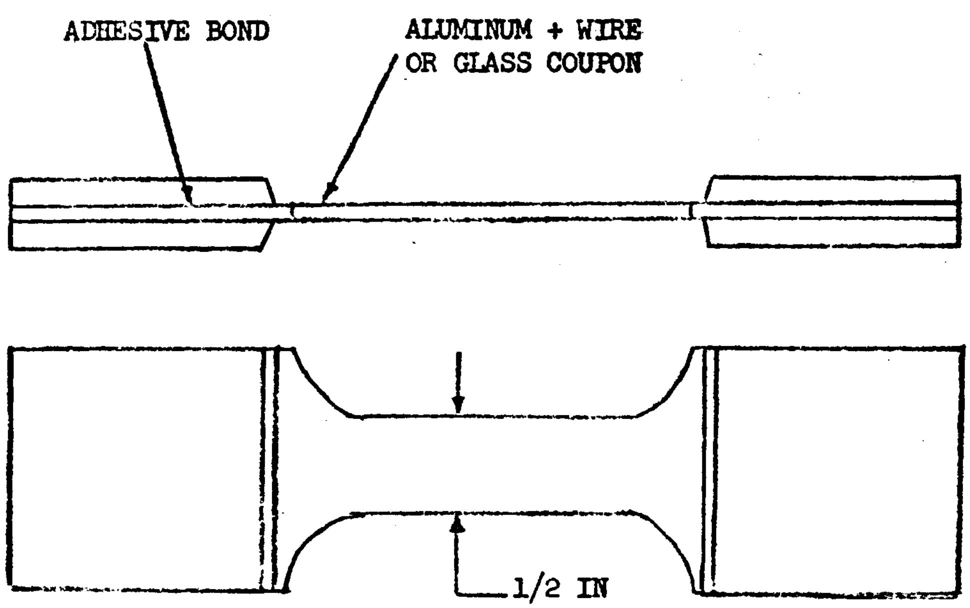
Δ = Core deflection (relative movement of the loading plates)

TESTS AT -423 F AT NASA/MSFC

Facing tensile, flatwise compression, and edgewise compression tests were conducted generally in accordance with the procedures described in Reference (e).

Flatwise tension and core shear tests were conducted generally in accordance with References (a) and (b). Shear loads were applied by a tension loading fixture.

The specimens subjected to the above tests at NASA/MSFC were furnished by NAA/LAD and, are, of the same configurations as described for tests at 212 F through -320 F, at NAA/LAD. An exception is the facing tension specimen. For these tests rectangular blanks with end tabs were furnished by NAA/LAD and machined at NASA/MSFC to the configuration shown below:



REFERENCES

(a) MIL-STD 401a, "Military Sandwich Constructions and Core Materials; General Test Methods"

(b) Fed., Test Methods Std. No. 151a, "Metals; Test Methods"

(c) MIL-STD-406, "Plastics; Methods of Testing"

(d) ASTM Specification C-237-61 "Core Shear Testing"

(e) IN-P & VE-M-63-12 "Low Temperature Properties of Composite Sandwich Constructions SATURNS-IV Common Bulkhead Type. O.Y. Reese and C.R. Denaburg 25 October 1963.

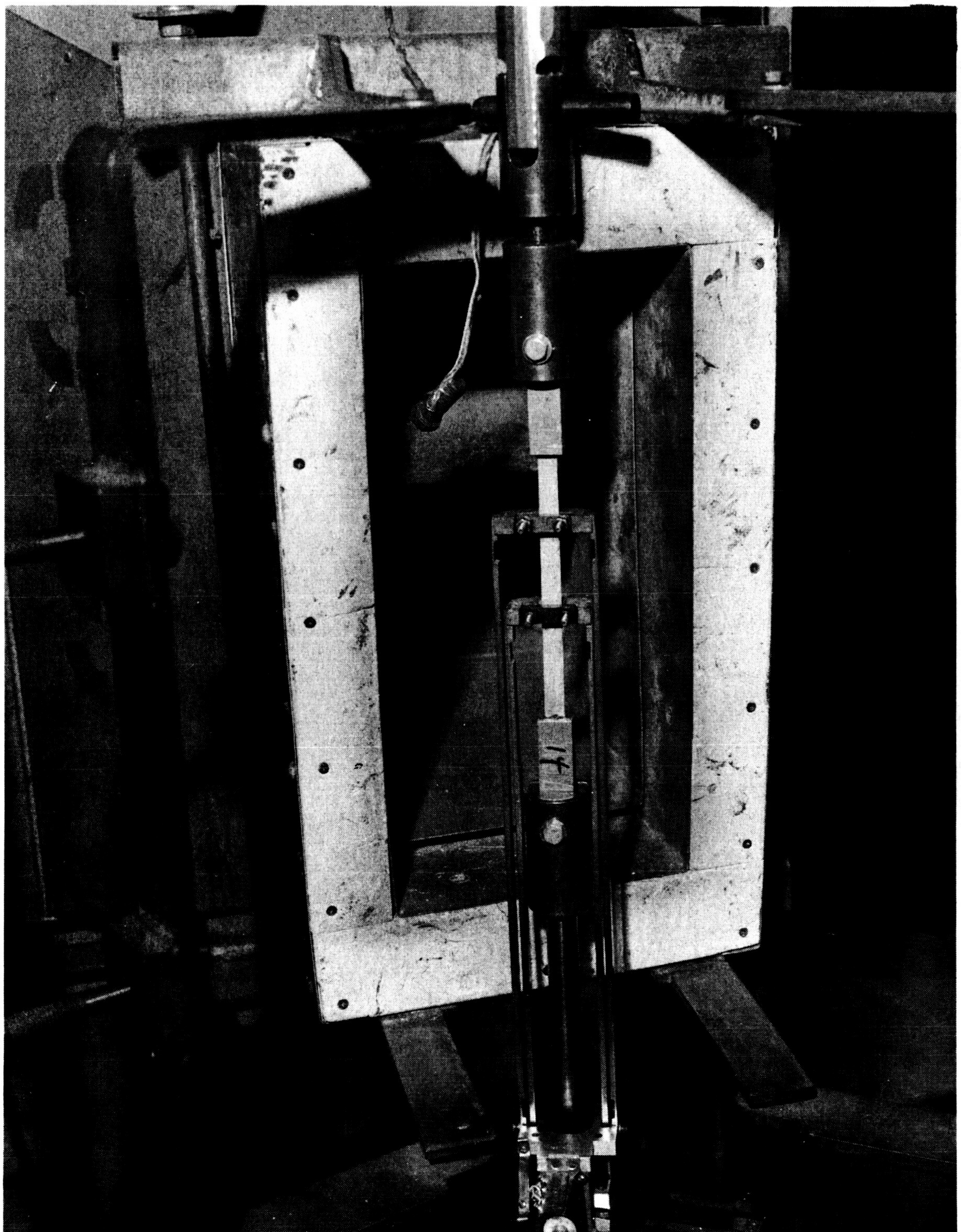


Figure 1 Hot Air Furnace. Facing Tension Test, Elevated Temperature Set-Up

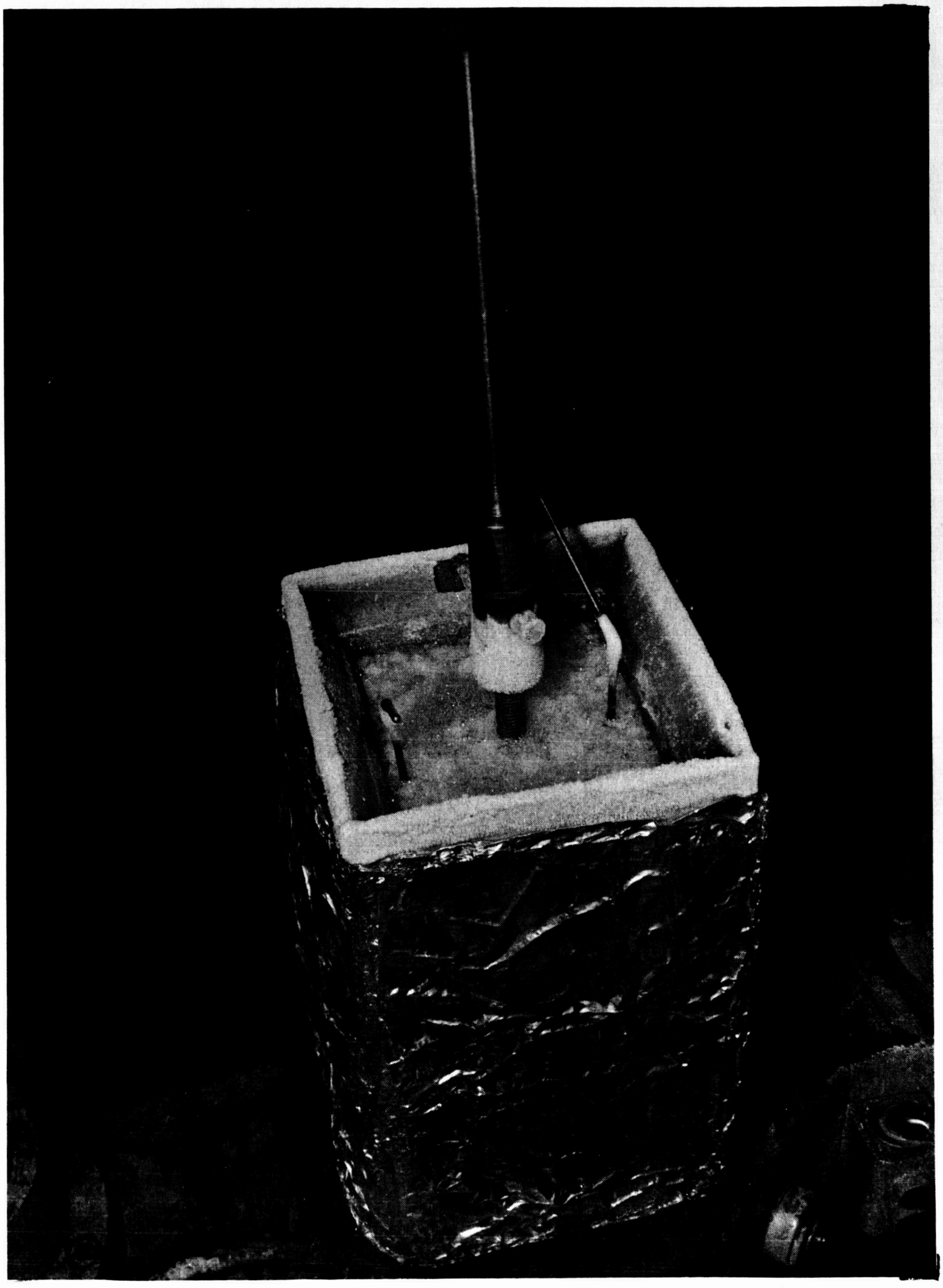


Figure 2 Liquid Immersion for -109F Testing

OK

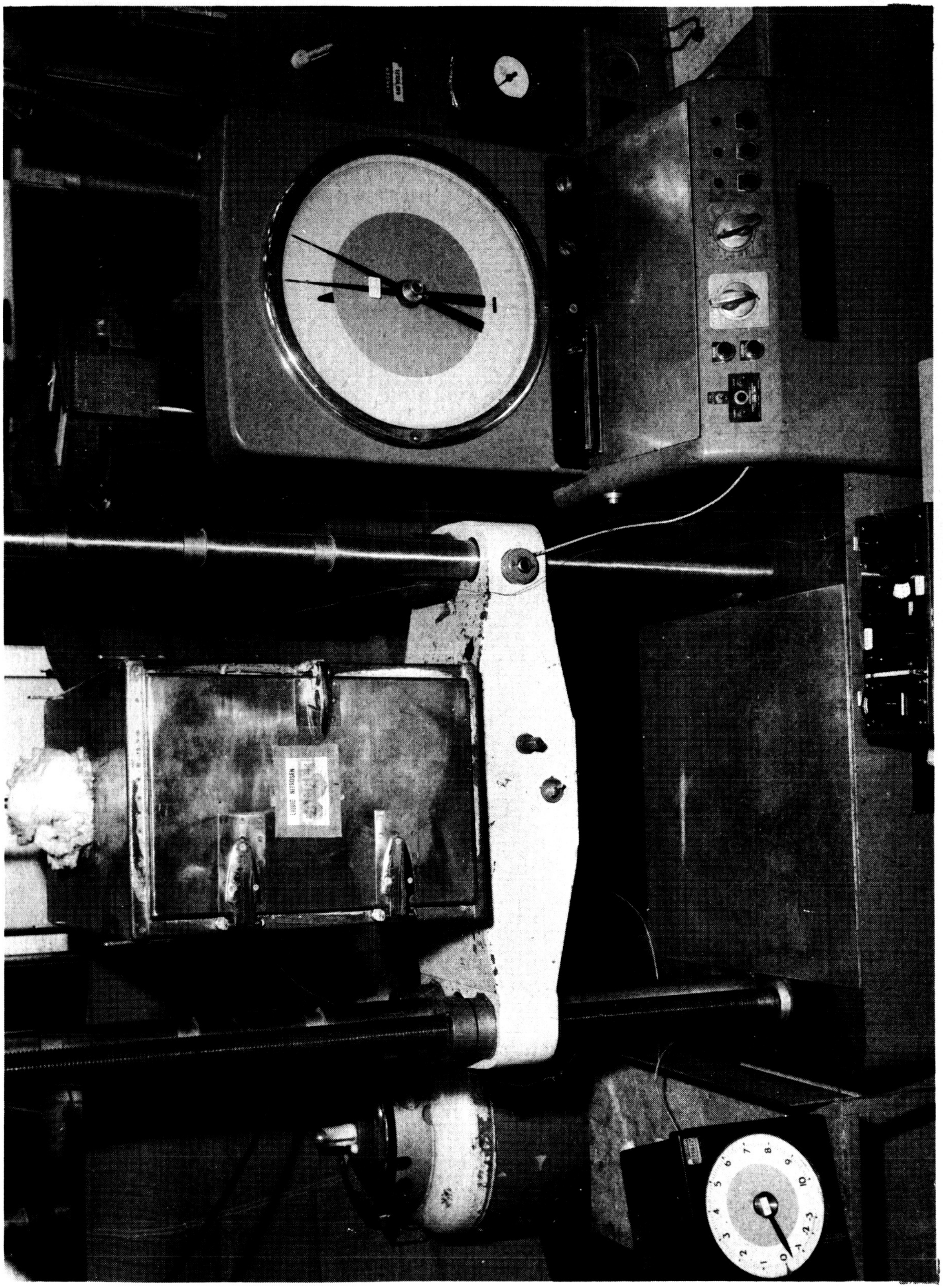


Figure 3 Gas Chamber for -109F Testing

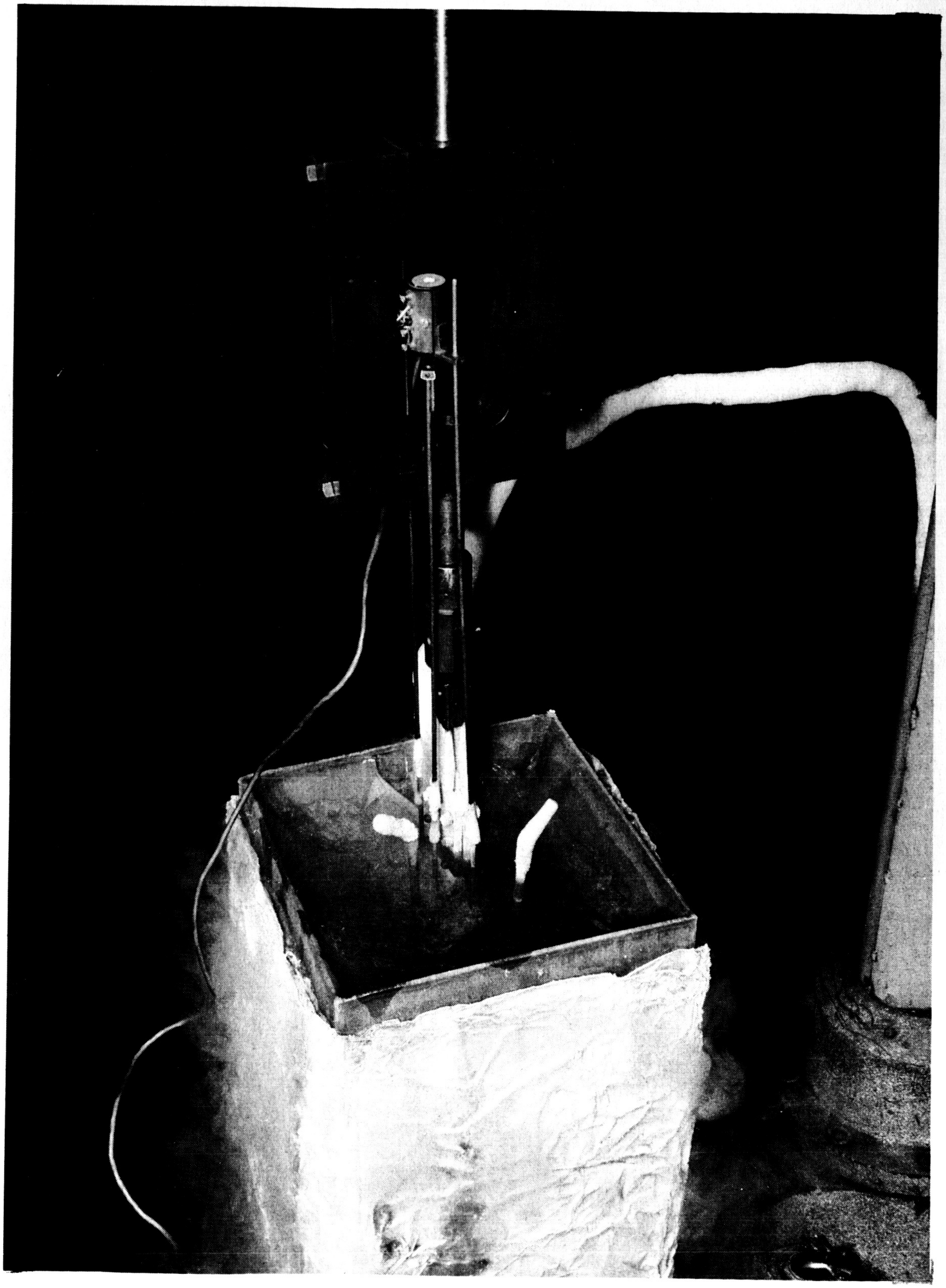


Figure 4 Liquid Immersion for -320F. Facing Tension Test Set-Up

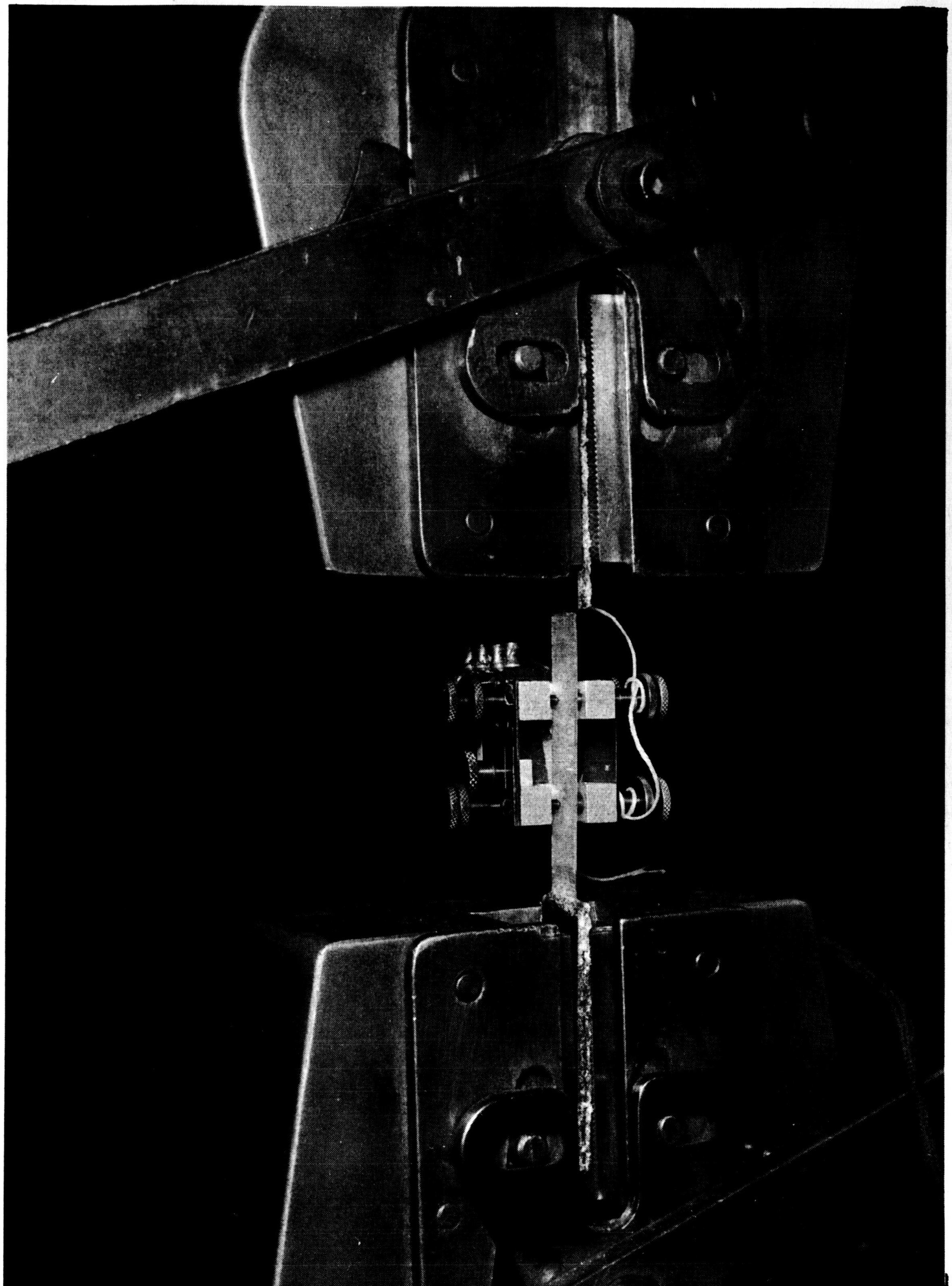


Figure 5 Facing Tension Test, Room Temperature Set-Up

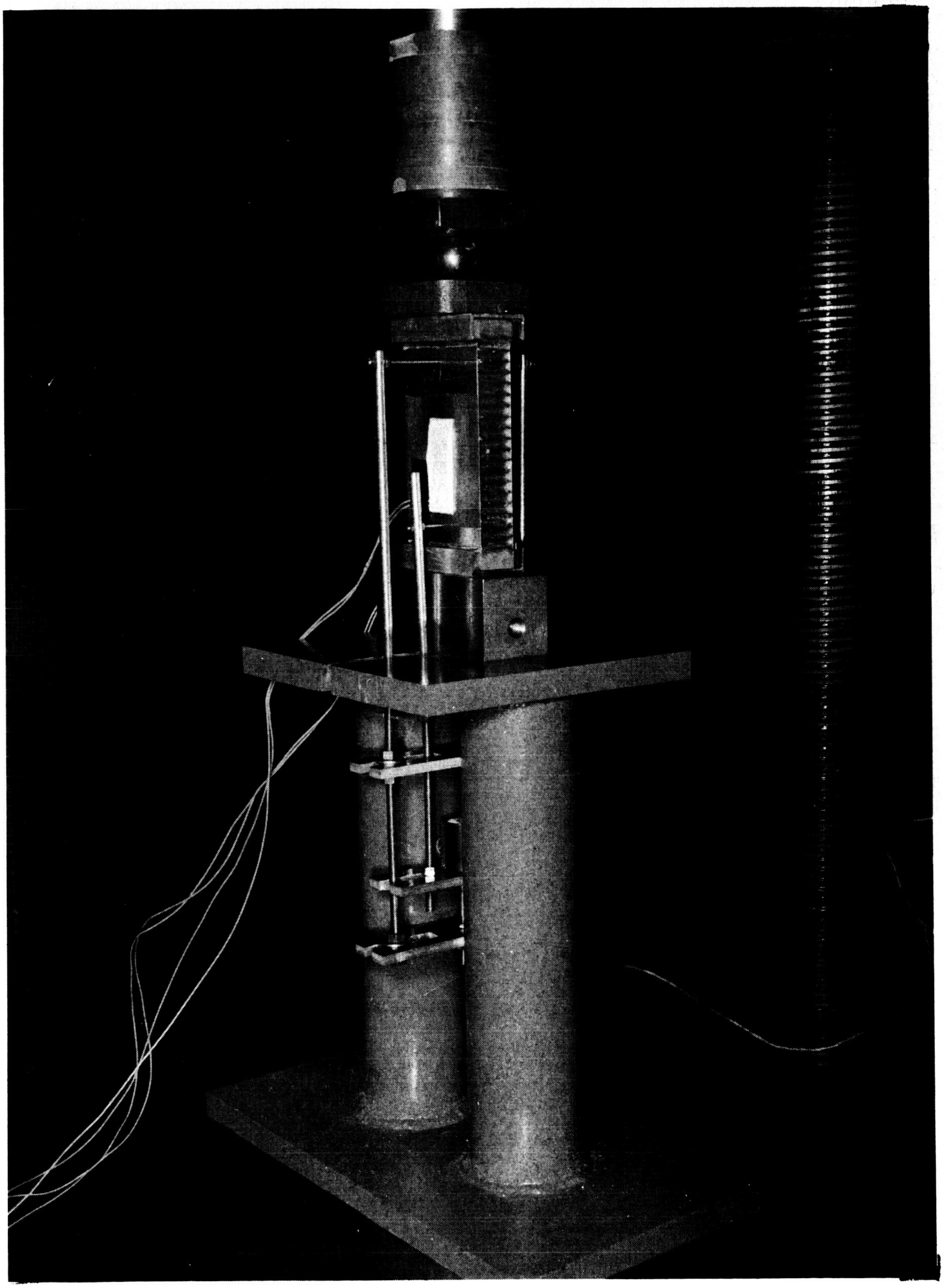


Figure 6 Edgewise Compression Test,
Room Temperature Set-Up

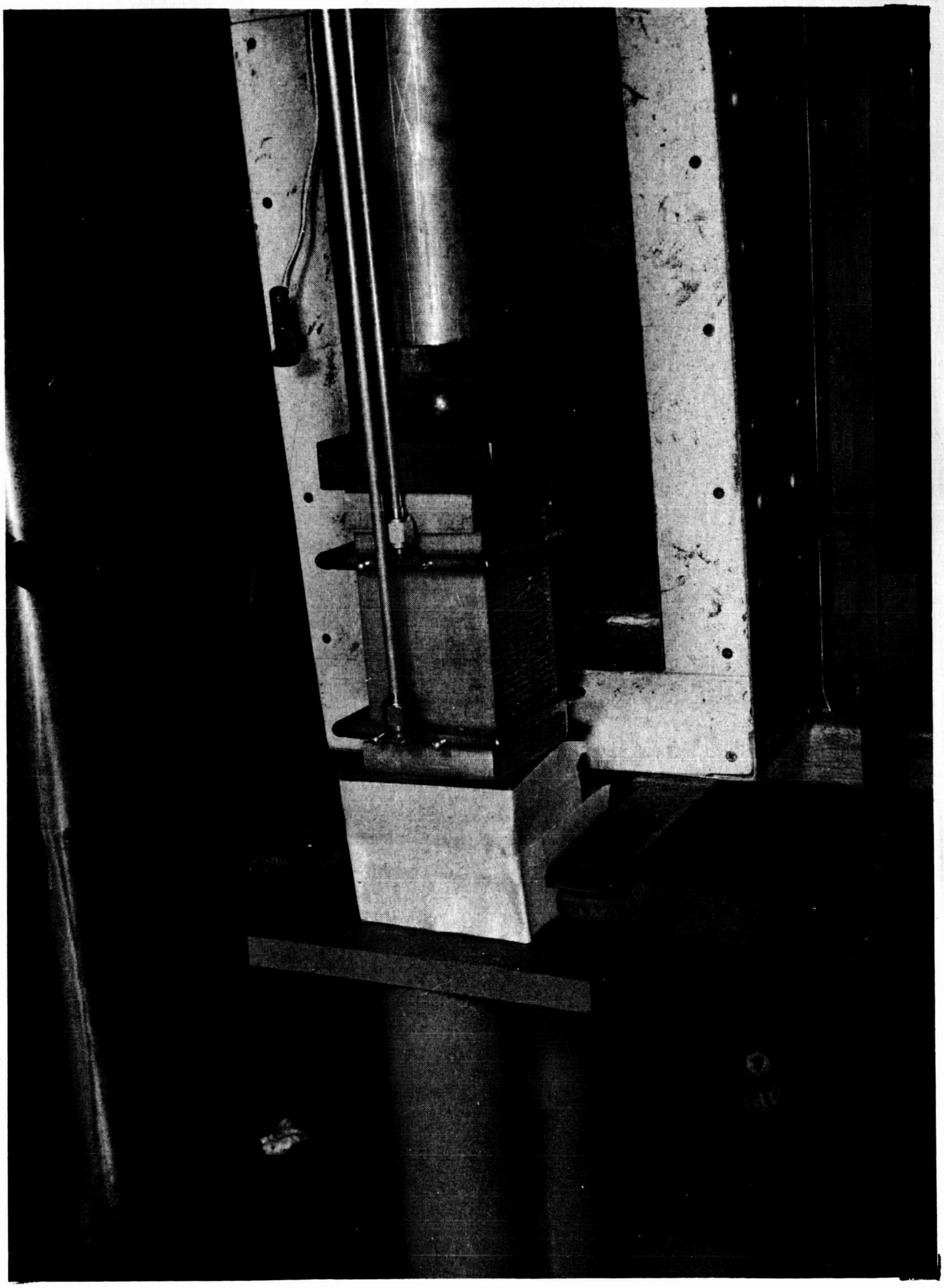


Figure 7 Edgewise Compression,
Elevated Temperature Set-Up

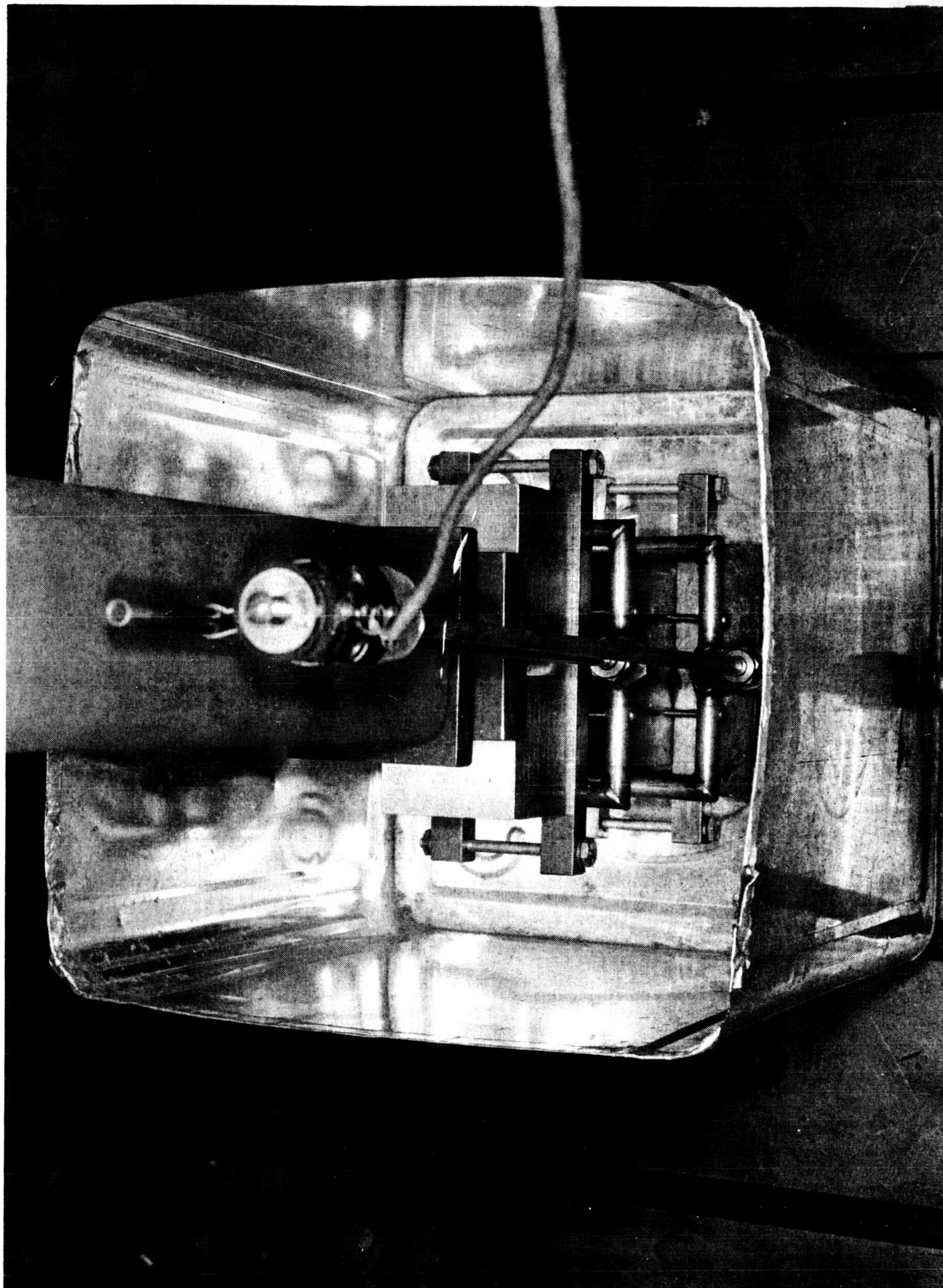


Figure 8 Edgewise Compression, Cryogenic Set-Up

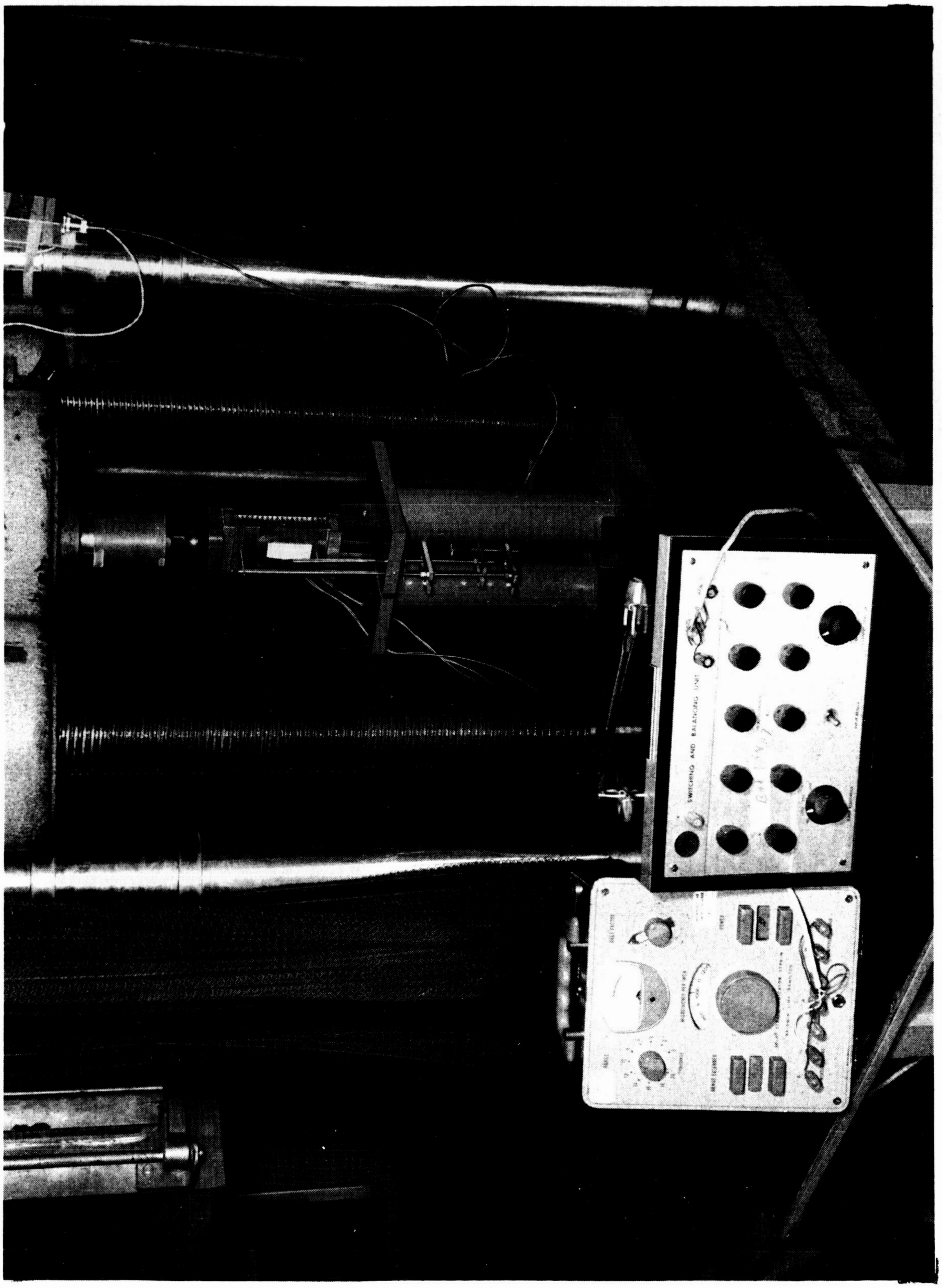


Figure 9 Edgewise Compression Test - Mechanical Deflectometer, Strain Gages, and Strain Gage Instrumentation

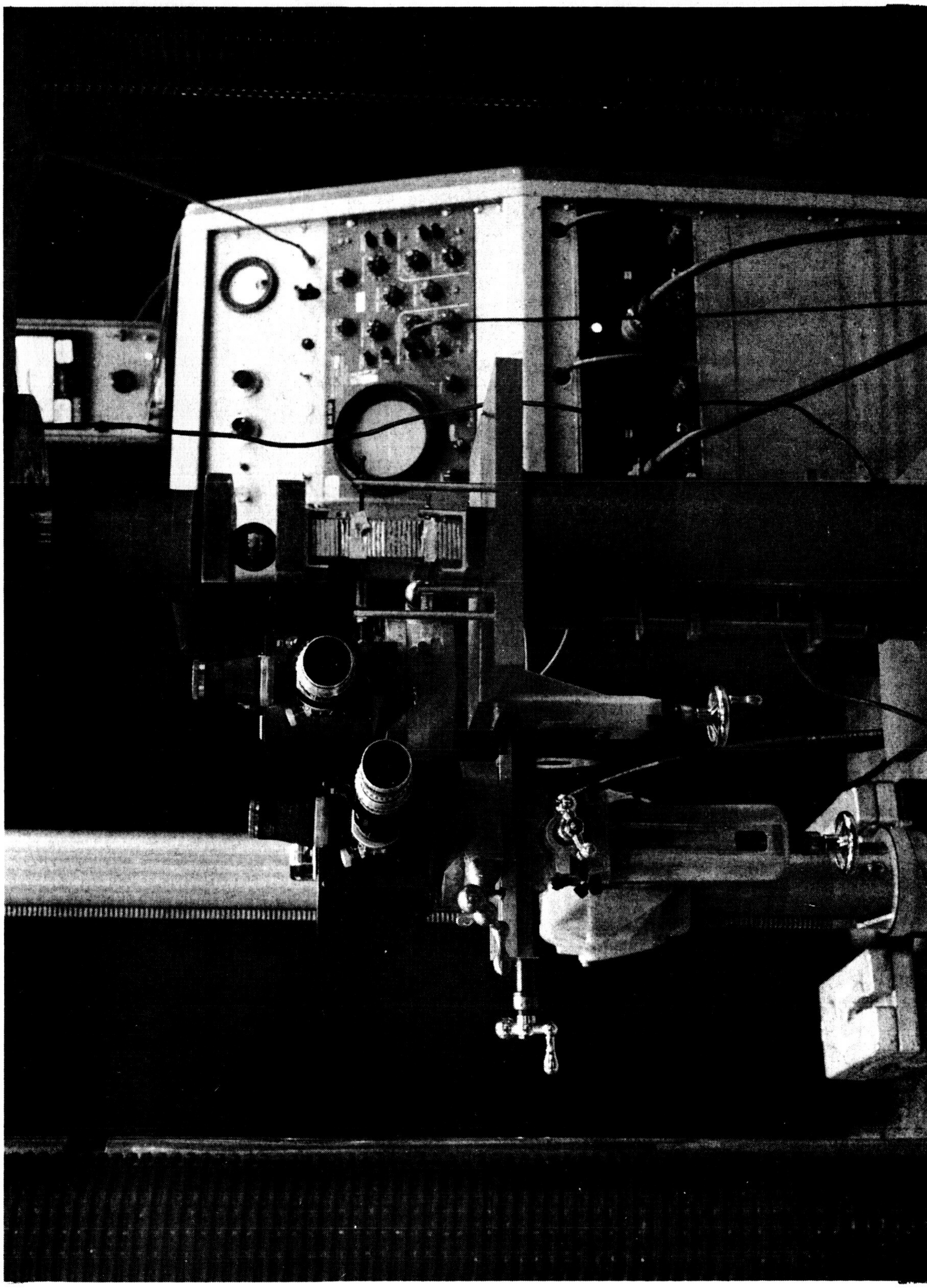


Figure 10 Edgewise Compression Test - OPTRON Set-Up

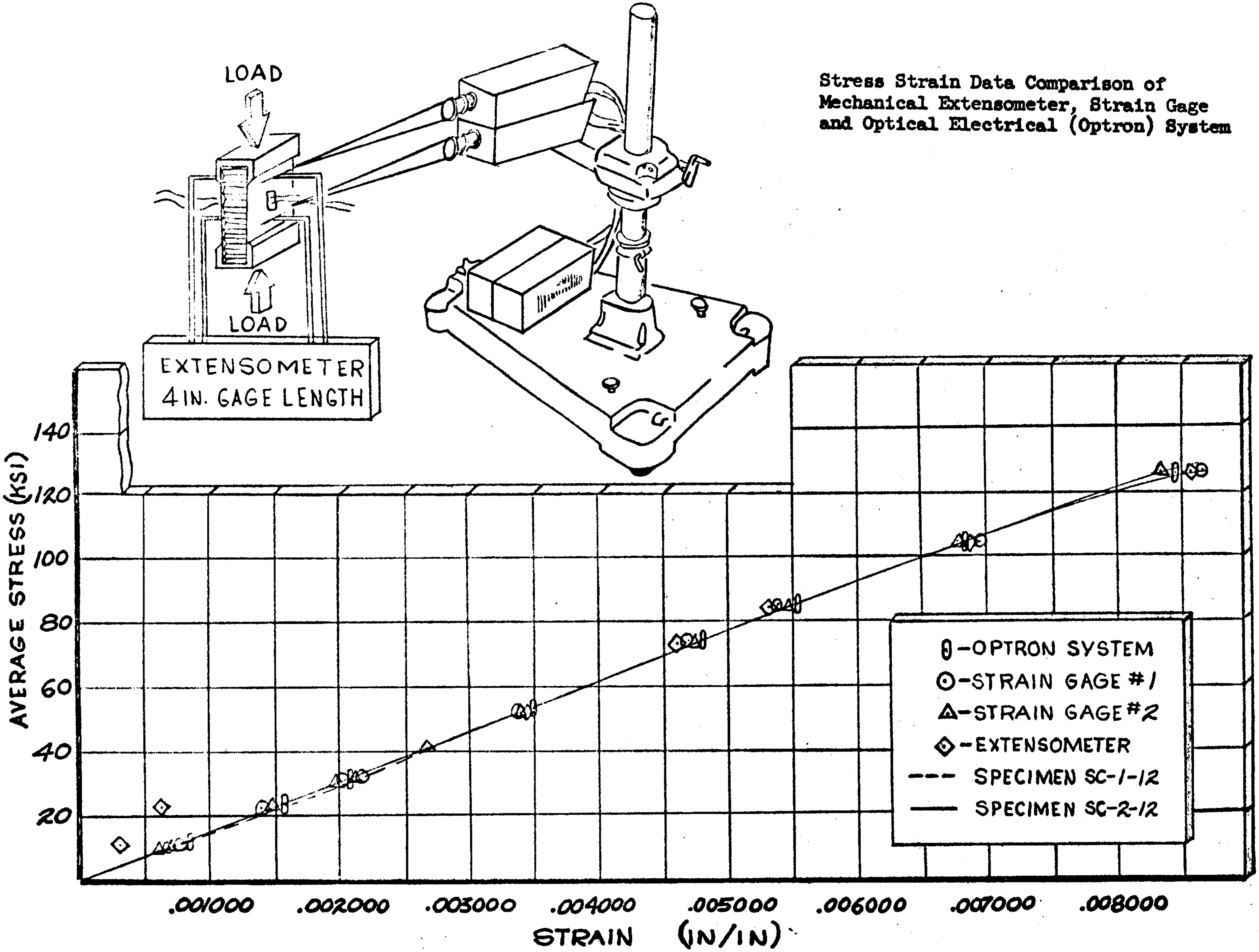


Figure 11. Strain Measurement Check

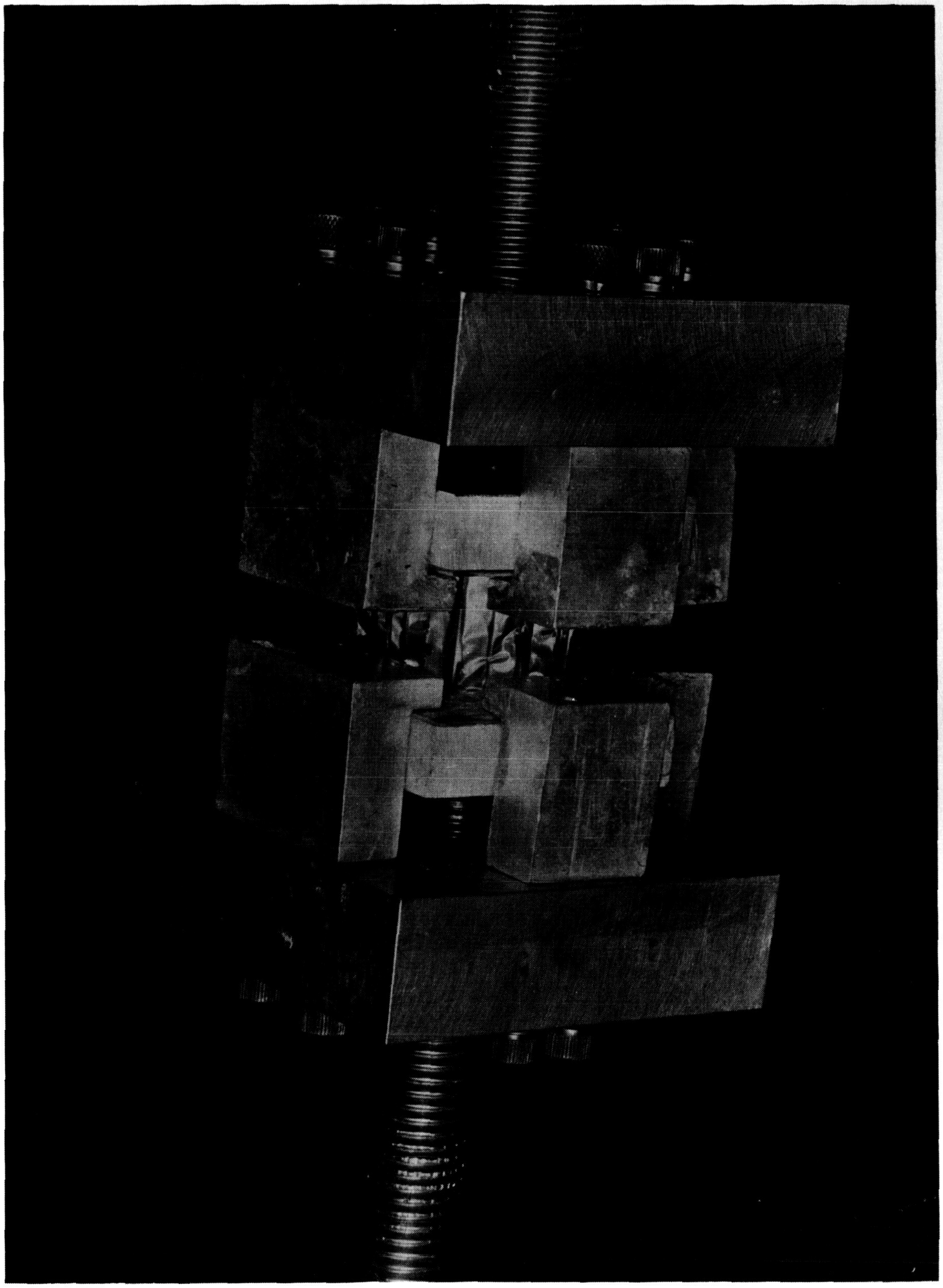


Figure 12 Flatwise Tension Test Set-Up

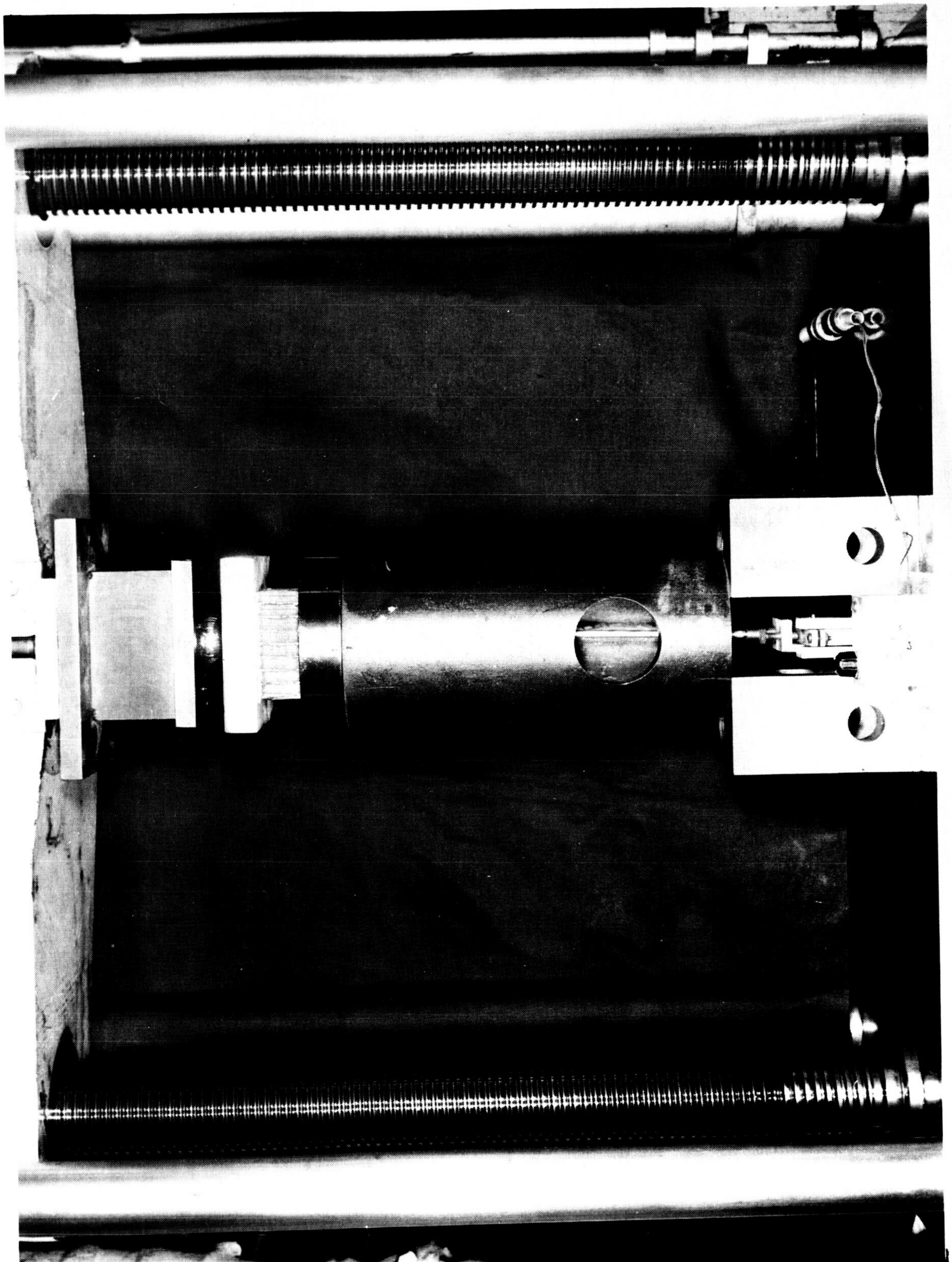


Figure 13 Flatwise Compression Test, Room Temperature Set-Up

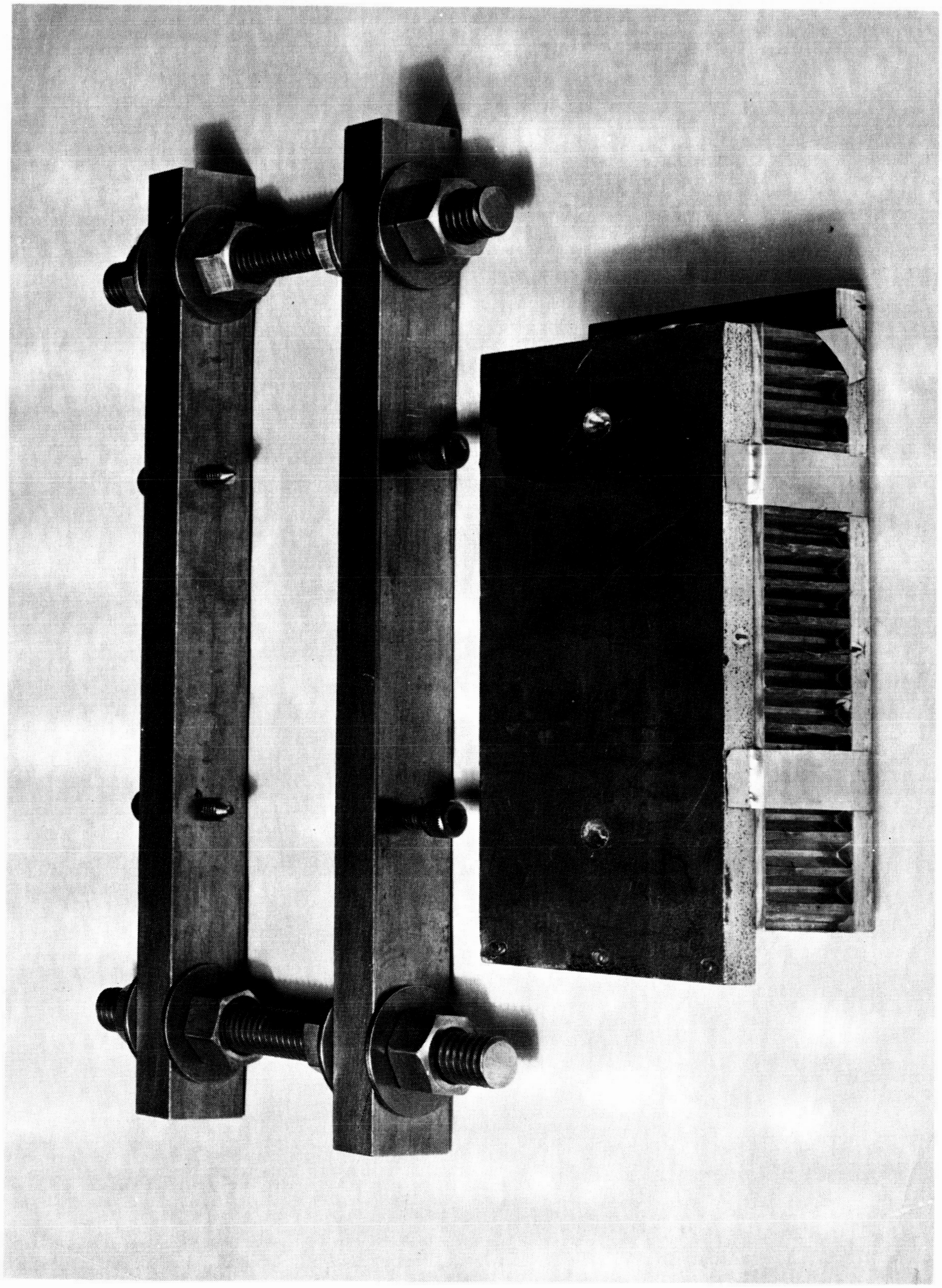


Figure 14. Core Shear Specimen
and Bonding Fixture

OK

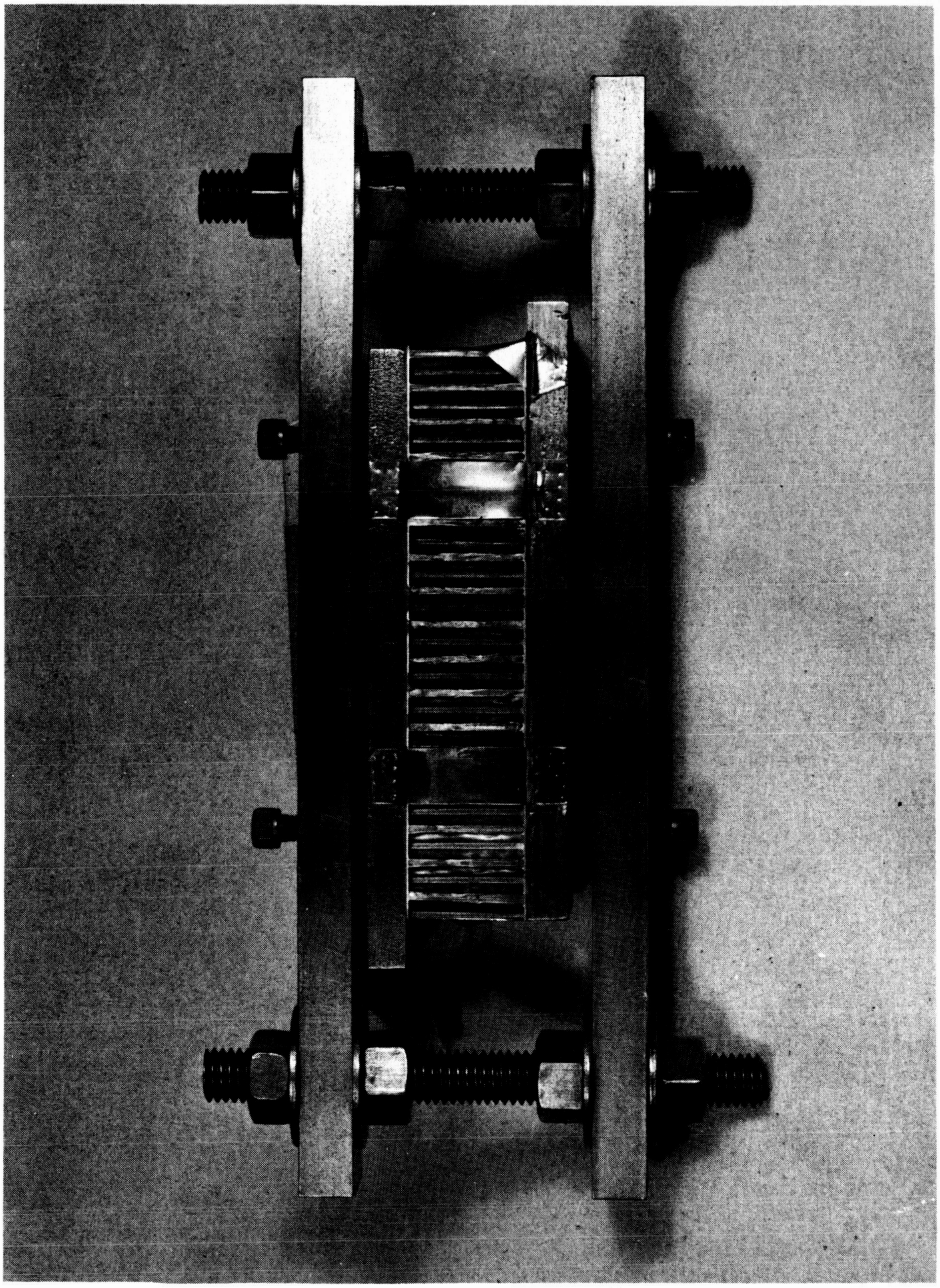


Figure 15 Core Shear Specimen and Bonding Fixture, Assembled

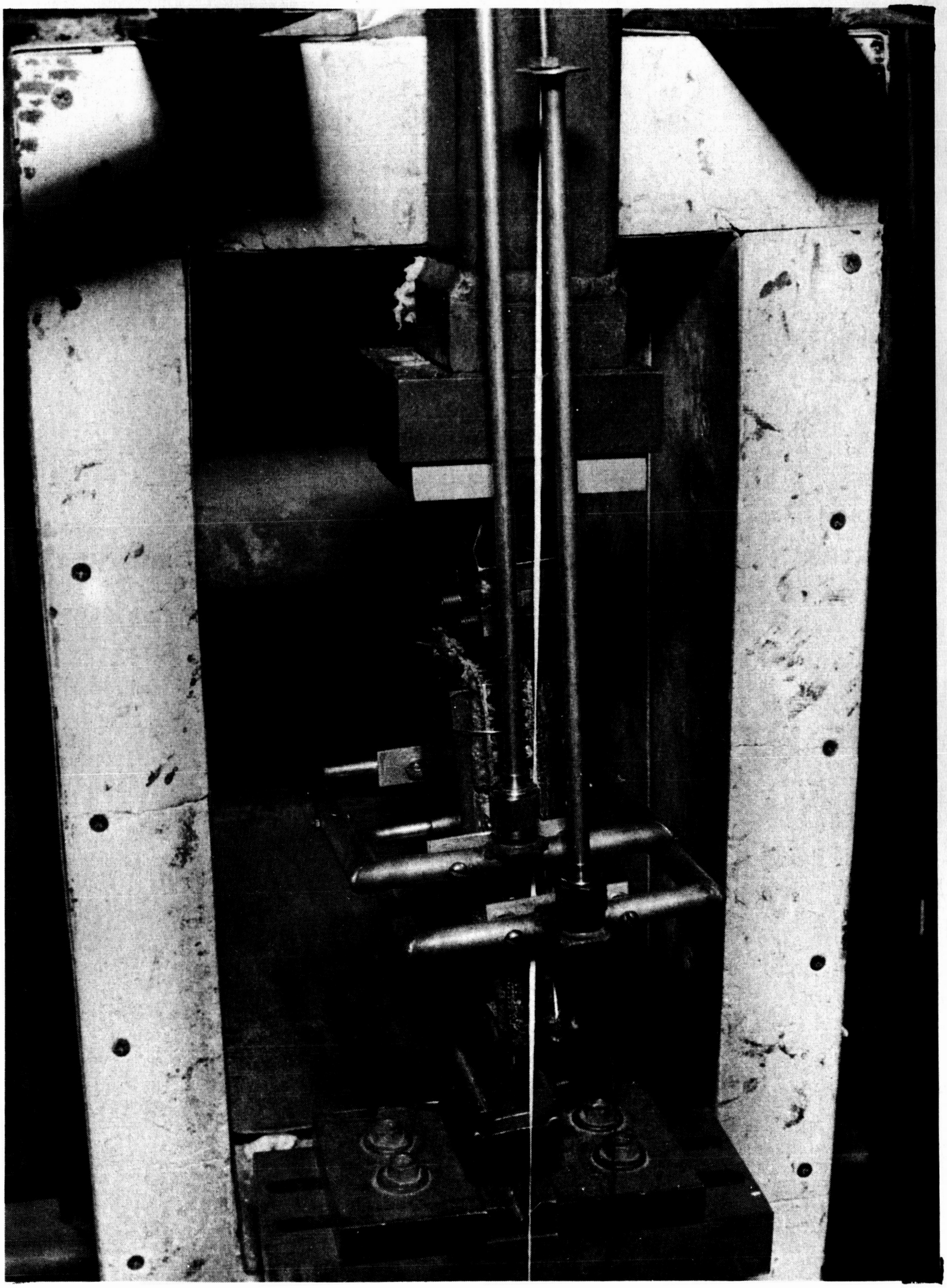
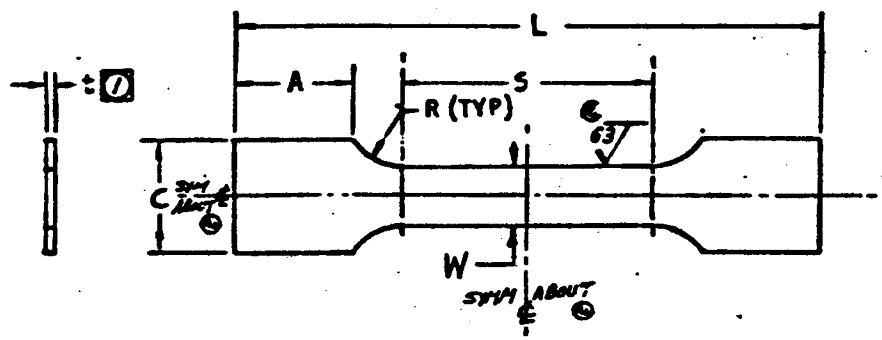


Figure 16 Core Shear Test, Loading and Deflectometer Set-Up

A | TT-11010

NOTICE OF CHANGE

ZONE	EFFECT ON		DISPOSITION & REFERENCES
A	1. REVISED NOTES; ADDED NOTES 3, 4, 5, 7 & 9. IN TABLE [illegible]	3	[illegible]
	2. ADDED 63 √, SYM ABOUT ℄ [illegible]	5	[illegible]



1 GRAIN DIRECTION

DASH NO.	WIDE	A	S	C	R	L
-15	.500	1	2	1	1/2	5
-13	.500	1	1 1/2	1	1/2	4 1/2
-11	.500	1	1	1	1/2	4
-9	.437	1	7/8	7/8	7/16	3 1/2
-7	.375	7/8	1/2	3/4	3/8	3
-5	.312	11/16	1/2	5/8	5/16	2 1/2
-3	.250	1/2	1/2	1/2	1/4	2

8. BLANK WIDTH 1/32 GREATER FOR .062 & UNDER & 1/16 GREATER FOR OVER .062

7. ALL MACHINED SURFACES 125√

6. IDENTIFY PER SPEC FAG-5A

5. MACHINE PER NAA SPEC FAG-125

1 4. SEE ATTACHED INSTRUCTION SHEET

3. EDGES OF REDUCED SECTION MUST BE PARALLEL WITHIN .0015

2. EDGES OF REDUCED SECTION TO BE LEFT SHARP ON ALL FLAT SURFACES

1. NO UNDERCUTTING OF RADIUS.

NOTE: UNLESS OTHERWISE NOTED

2 9. HEAT TREATMENT TO BE PERFORMED PRIOR TO FINISH MACHINING

PART NO.	NO. REQ.	PART NO	NO. REQ.	DESCRIPTION	SIZE	ZONE	SPECIFICATION	NO. REQ. SHIP	NEXT ASSEM.	MODEL
		-15		SPECIMEN	t x 1 x 5					
		-13			t x 1 x 4 1/2					
		-11			t x 1 x 4					
		-9			t x 7/8 x 3 1/2					
		-7			t x 3/4 x 3					
		-5			t x 5/8 x 2 1/2					
		-3		SPECIMEN	t x 1/2 x 2					
R. H. ASSEM.		L. H. ASSEM.		MATERIAL						

HEAT TREAT: 1 2
CALC WT.
DRAWN BY [illegible] 7-21-55 CHECKER [illegible] 7-25-55 APPROV. [illegible]

FINISH: 1
SCALE: NOTED
DWG. SIZE: B

TOLERANCES EXCEPT AS NOTED
ANGLES ± 1/2 DEG.
FRACTIONS ± 1/32
DECIMALS ± .010
√ SURFACE ROUGHNESS PER NATL. AIRCRAFT STANDARD 730

DRILLED HOLES
.040 TO .1285 DIA. +.002, -.001
.136 TO .228 DIA. +.003, -.001
.234 TO 1/2 DIA. +.004, -.001
33/64 TO 3/4 DIA. +.005, -.001
49/64 TO 1" DIA. +.007, -.001
1-1/64 TO 2" DIA. +.010, -.001

NORTH AMERICAN AVIATION, INC.
INTERNATIONAL AIRPORT
LOS ANGELES 45, CALIFORNIA

SPECIMEN-FLAT SUB-SIZE TENSION TEST ROOM TEMPERATURE

TT-11010

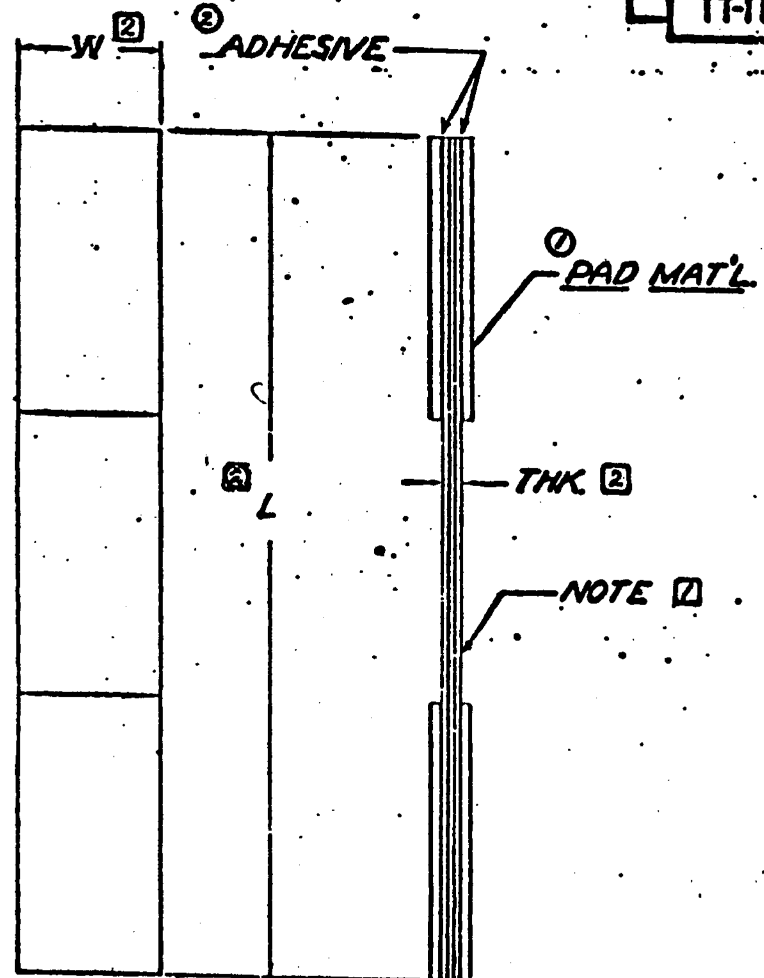
8E

Req. 34315-5482

TT-16812

FOR INFORMATION
WILL NOT BE MAINTAINED UP TO DATE

TT-16812



(WOUND GLASS COMPOSITE FACE SHEET)

2 MAX. DIM. FOR TEST REQ'TS.
W - 3/4 L - 10 THK. - 0.125
1 LAMINATED MATERIAL

☐ NOTES

REQD	REQD	PART NUMBER	DESC	MATERIAL	SIZE	ZONE	MATL SPEC	LINE
		②	ORGANIC ADHESIVE				BONDMASTER 611 (OR MIN. R.T. LAP SHEAR - 3000 PSI)	
	4	①	ASBESTOS	GASKET MAT'L.			RAYBESTOS NO. KGD.	001 OR EQUIV.

LIST OF MATERIAL

DRILLED HOLE TOLERANCES	
.040 TO .1285	+.002 -.001
.136 TO .228	+.003 -.001
.234 TO 1/2	+.004 -.001
33/64 TO 3/4	+.005 -.001
49/64 TO 1	+.007 -.001
1-1/64 TO 2	+.010 -.001

TOLERANCES EXCEPT AS NOTED: ANGLES ±1/2°, FRACTIONS ±1/32, DECIMALS ±.010
SURFACE ROUGHNESS PER MIL-STD-10 (FAG-219)
HEAT TREAT
FINISH

DATE	4-29-64
DR BY	H. LAIRD
CHK BY	[signature]
APPD BY	[signature]
APPD BY	

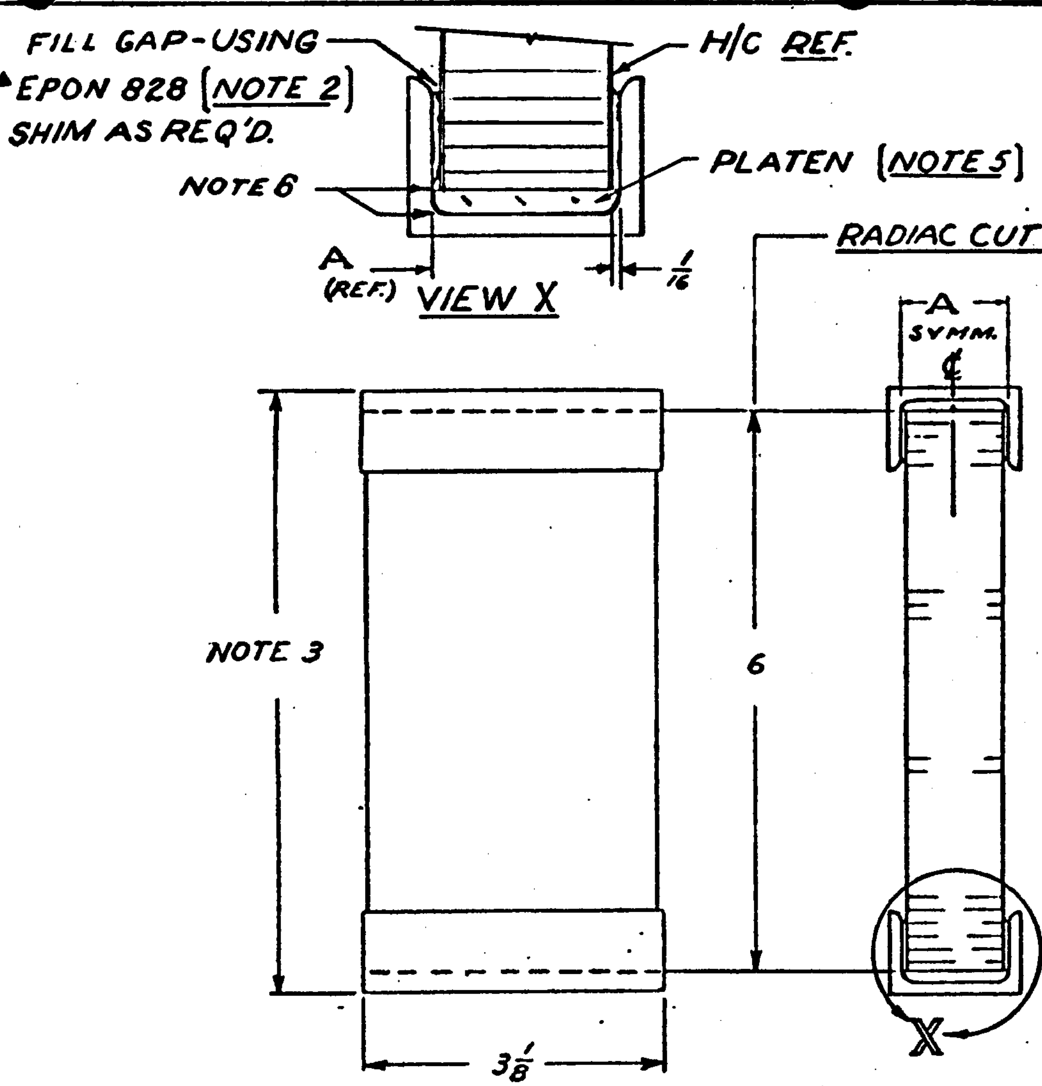
INSPECT PER MIL-I-6870 LQ0091-007 CLASS

SPECIMEN - LAMINATED MATERIAL, TENSION TEST

USED ON | NEXT ASSY — APPLICATION

NORTH AMERICAN AVIATION, INC.
ENGINEERING
INTERNATIONAL AIRPORT
LOS ANGELES 45, CALIF.

DWG SIZE C | TT-16812 | SCALE | WT | SHEET OF



FOR INFORMATION
WILL NOT BE MAINTAINED UP TO DATE

TT-16808

6. SPECIM. & CHANNEL BEARING SURF.
5. USE PLATEN AS REQ'D. TO CLEAR RAD.
▲ 4. MFG. BY SHELL CHEM. CO.
3. LOADING ENDS PARALLEL WITHIN .001 IN. PER IN.
2. USE DIETHYLENE TRIAMINE AS CAT. WITH EPON 828 SEE MFG. SPEC.
1. PLATEN TO HAVE 100% BEARING ON LOADING SURFACES. (SPECIM. & CHANNEL)

NOTES

REQD RH	REQD LH	PART NUMBER	DESC	MATERIAL	SIZE	ZONE	MATL SPEC	LINE	QTY PER END ITEM	USED ON	NEXT ASSY
	4		SHIM	ALUM. ALLOY							
	2		PLATEN	MILD STEEL							
	2		CHANNEL	" "				001			

LIST OF MATERIAL — APPLICATION

DRILLED HOLE TOLERANCES	
.040 TO .1285	+.002 -.001
.136 TO .228	+.003 -.001
.234 TO 1/2	+.004 -.001
33/64 TO 3/4	+.005 -.001
49/64 TO 1	+.007 -.001
1-1/64 TO 2	+.010 -.001

TOLERANCES EXCEPT AS NOTED: ANGLES ±1/2°, FRACTIONS ±1/32, DECIMALS ±.010
SURFACE ROUGHNESS PER MIL-STD-10 (FAG-219)
HEAT TREAT
FINISH

DATE	2 APRIL 64
DR BY	V. LAIRD
CHK BY	R. Hickey
APPD BY	M. Rutledge
APPD BY	

INSPECT PER MIL-I-6870 LOOSOI-007 CLASS 1

SPECIMEN- HONEYCOMB EDGEWISE COMPRESSION TEST, CHANNEL FACE

SCALE FULL — WT

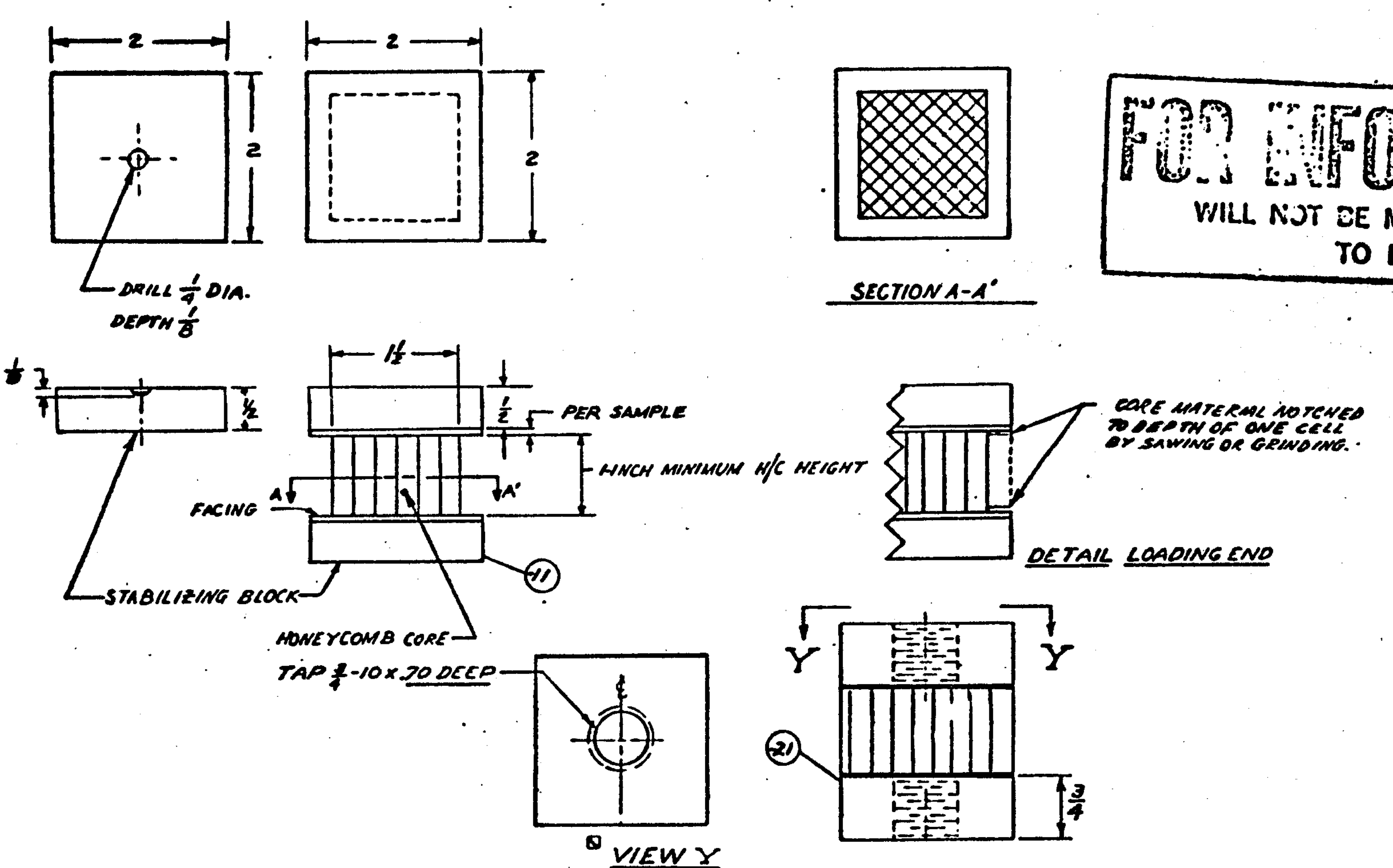
NORTH AMERICAN AVIATION, INC.
ENGINEERING
INTERNATIONAL AIRPORT
LOS ANGELES 45, CALIF.

DWG SIZE C — TT-16808 — SHEET OF

NA-63-1358-13

TT-14336

SYM	DESCRIPTION	DISPOS	DATE	SIGNATURE
	1 MAY BE REWORKED 4 RECORD CHANGE 2 CANNOT BE REWORKED 5 NOW SHOP PRACTICE 3 PARTS MADE OK			



FOR INFORMATION
WILL NOT BE MAINTAINED UP TO DATE

TT-14336

4. BLOCKS ARE MILD STL. $2 \times 2 \times \frac{3}{4}$
3. CENTERING HOLES TO BE DRILLED IN STABILIZING BLOCKS PRIOR TO BONDING.
2. STABILIZING BLOCKS TO BE OF 7075 HEAT TREATED ALUMINUM $2 \times 2 \times \frac{1}{2}$.
1. STABILIZING BLOCK MAY BE BONDED WITH ANY ADHESIVE CAPABLE OF PROVIDING A MINIMUM LAP SHEAR STRENGTH OF 2,000 PSI AT ROOM TEMP.

REQD RH	REQD LH	PART NO.	DESC	MATERIAL	SIZE	ZONE	MATL SPEC	LINE	QTY PER END ITEM
		TT-14336-21		STL. BLOCK ASSY.					
		TT-14336-11		ALUM. BLOCK ASSY.				001	

LIST OF MATERIAL

USED ON	NEXT ASSY
APPLICATION	

DRILLED HOLE TOLERANCES
.040 TO .1285, +.002, −.001
.136 TO .228, +.003, −.001
.234 TO 1/2, +.004, −.001
33/64 TO 3/4, +.005, −.001
49/64 TO 1, +.007, −.001
1-1/64 TO 2, +.010, −.001

TOLERANCES EXCEPT AS NOTED: ANGLES ±1/2°, FRACTIONS ±1/32, DECIMALS ±.010

SURFACE ROUGHNESS PER MIL-STD-10 (FA6-219)

HEAT TREAT

FINISH

DATE	9 APRIL 64
DR BY	M. LAIRD
CHK BY	R. Hickey
APPD BY	[illegible]
APPD BY	

INSPECT PER MIL-I-6870 (L00501-0071) CLASS

SPECIMEN-HONEYCOMB SAND. FLATWISE TENSILE TEST

SCALE 1" = 1"

WT

NORTH AMERICAN AVIATION, INC.
ENGINEERING
INTERNATIONAL AIRPORT
LOS ANGELES 45, CALIF.

DWG SIZE C

TT-14336

TT-13175

REVISIONS				
SYM	DESCRIPTION	DISPOS	DATE	SIGNATURE
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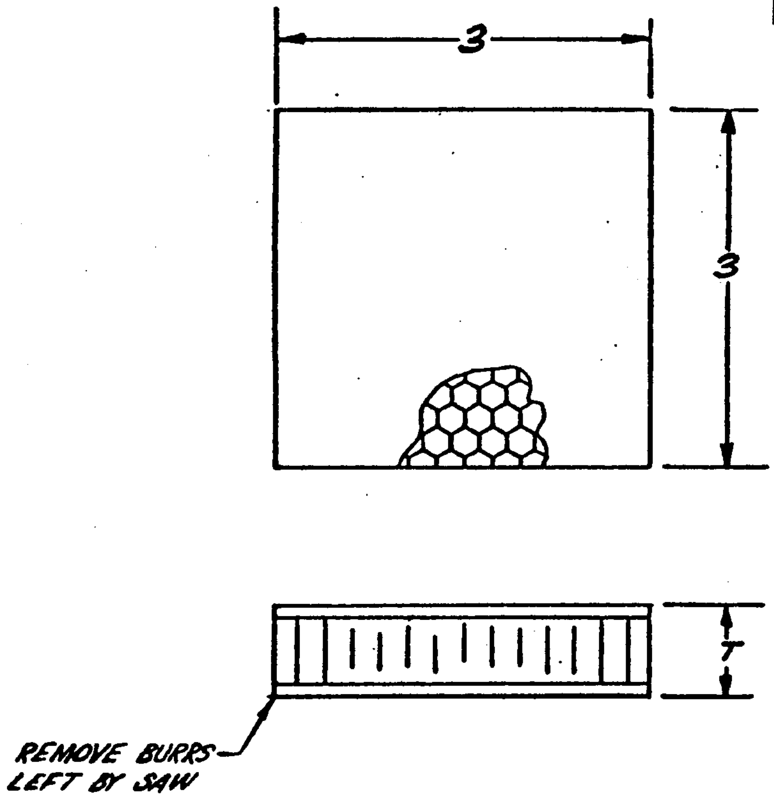

FOR INFORMATION
WILL NOT BE MAINTAINED UP
TO DATE

REQD RH	REQD LH	PART NO	DESC	MATERIAL	SIZE	ZONE	MATL SPEC	QTY PER END ITEM	USED ON	NEXT ASSY
			LIST OF MATERIAL						APPLICATION	

DRILLED HOLE TOLERANCES	
.040 TO .1285	+.002, −.001
.136 TO .228	+.003, −.001
.234 TO 1/2	+.004, −.001
33/64 TO 3/4	+.005, −.001
49/64 TO 1	+.007, −.001
1-1/64 TO 2	+.010, −.001

TOLERANCES EXCEPT AS NOTED
ANGLES ±1/2° FRACTIONS ±1/32 DECIMALS ±.010
√ SURFACE ROUGHNESS PER MIL-STD-10 (FA6-219)
HEAT TREAT
FINISH

DATE	4-30-58
DR BY	A. TUNGSETH
CHK BY	E. Kuthasky
APPD BY	
APPD BY	

SPECIMEN – HONEYCOMB FLATWISE COMPRESSION TEST

SCALE FULL WT

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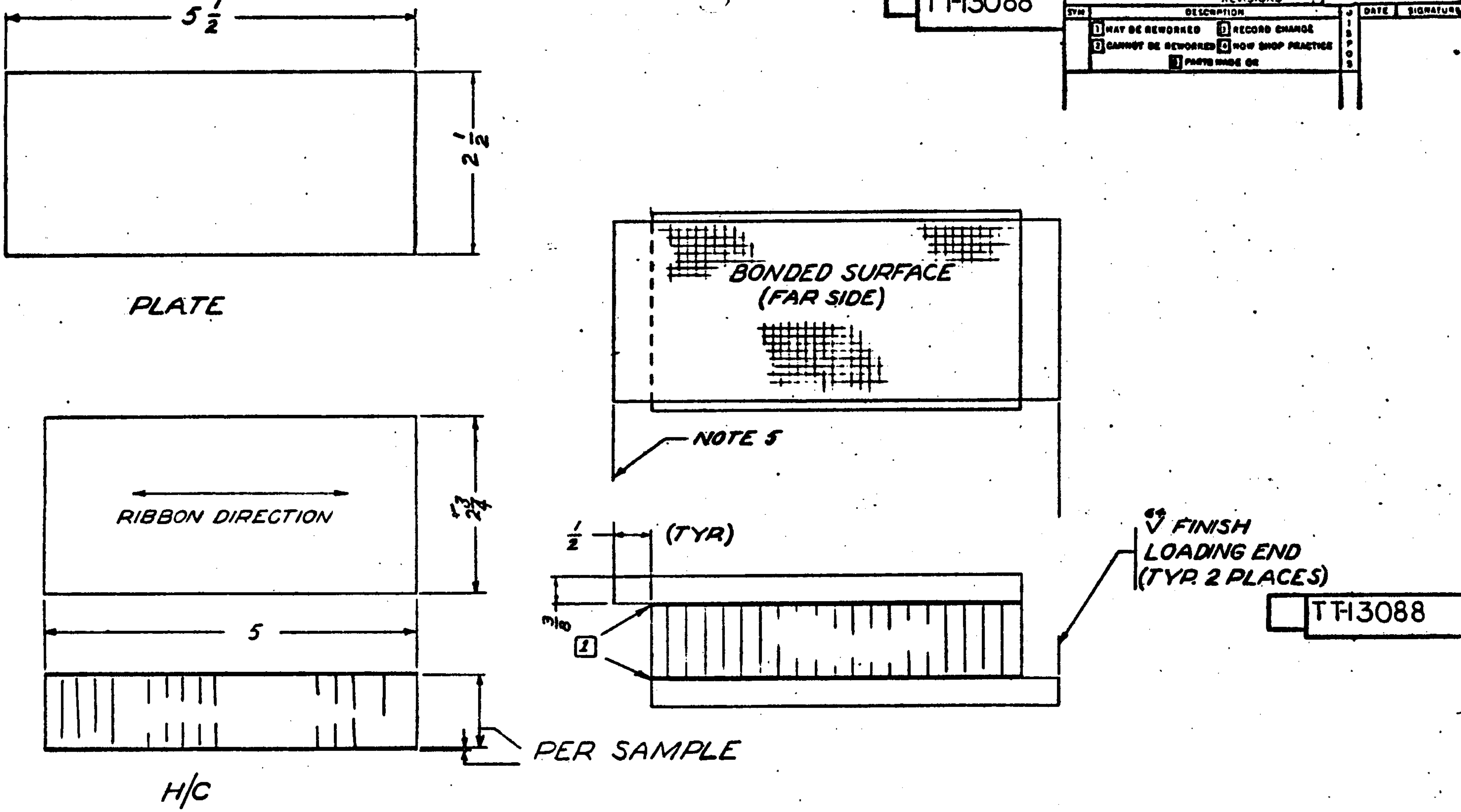
INTERNATIONAL AIRPORT
LOS ANGELES 45, CALIF.

DWG SIZE B TT-13175

3. IF NECESSARY, SIZE OF SPECIMEN MAY BE REDUCED TO 2 x 2 MIN.
2. SAW SPECIMENS FROM FABRICATED PANELS TOLERANCE ± 1/16
1. DO NOT CRUSH
NOTES: UNLESS OTHERWISE NOTED

TT-13088

SYM	DESCRIPTION	J I S P O S	DATE	SIGNATURE
	REVISIONS 1 MAY BE REWORKED 2 CANNOT BE REWORKED 3 RECORD CHANGE 4 NOW SHOP PRACTICE 5 PHOTO MADE OK			



NOTES—

1. LOADING ENDS PARALLEL WITHIN .001 IN. PER IN.
2. DO NOT CRUSH.
3. DO NOT BREAK LOADING EDGES.
4. SPECIMEN MAY BE FRICTION SAWED IF TOL. OF ± 1/32 OBSERVED.
5. MILLING REQD. ON LDG. EDGES ONLY.
6. 1 ADHESIVE BOND MAT'L. MIN. SHEAR STRENGTH OF 4000 PSI. AT TEMP.

REQD RH	REQD LH	PART NUMBER	DESC	MATERIAL	SIZE	ZONE	MATL SPEC	LINE	QTY PER END ITEM	USED ON	NEXT ASSY
			BOND.	1							
	2		STAB. PL.	1020 STL OR EQ.	5 1/2 × 2 1/2 × 3/8						
	1		H/C CORE	SAMPLE	5 × 2 1/2			001			
			LIST OF MATERIAL							APPLICATION	

DRILLED HOLE TOLERANCES	
.040 TO .1285	+.002, -.001
.136 TO .228	+.003, -.001
.234 TO 1/2	+.004, -.001
33/64 TO 3/4	+.005, -.001
49/64 TO 1	+.007, -.001
1-1/64 TO 2	+.010, -.001

TOLERANCES EXCEPT AS NOTED: ANGLES ±1/2°, FRACTIONS ±1/32, DECIMALS ±.010

SURFACE ROUGHNESS PER MIL-STD-10 (FA5-219)

HEAT TREAT

FINISH

DATE	4-13-64
DR BY	M. LAIRD
CHK BY	P. Hickman
APPD BY	[illegible]
APPD BY	

INSPECT PER MIL-I-6870 (LQ0501-007 CLASS)

SPECIMEN - FACE STABILIZED H/C PLATE SHEAR TEST

SCALE FULL   WT

NORTH AMERICAN AVIATION, INC.
ENGINEERING
INTERNATIONAL AIRPORT
LOS ANGELES 45, CALIF.

DWG SIZE C   TT-13088   CODE IDENT 43999   SHEET OF

Appendix E

CONSTRUCTION OF COMPOSITE STRESS-STRAIN CURVES

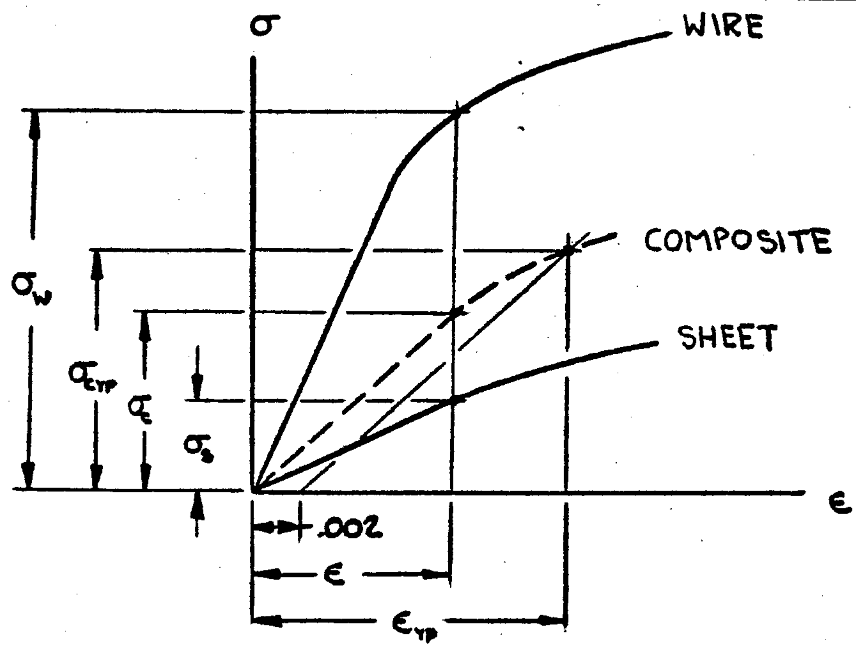
The construction of tension stress-strain curves of the sheet-wire composites is based on the assumption that the load-carrying ability of the composite is the sum of the load-carrying abilities of the metals, with no contribution from the resin. Hence, two composites with the same cross-sectional area of wire and metal sheet, but with different amounts of resin, will have the same load-deflection curves.

Using the notation of figure 1, loads in the composite (P_ϵ) at various strains (ϵ) are calculated from the formula

$$P_\epsilon = \sigma_w A_c \left[K + p\,(1 - K) \right] \tag{1}$$

The stresses (σ_c) corresponding to the strains are obtained by dividing equation (1) by the composite area (A_c). Such calculated pairs of stresses and strains determine a stress-strain curve which neglects any effect the resin may have on composite thickness. To construct the stress-strain curve of a composite based on the physical area of the composite, including any area added by the resin, the thickness of the actual composite, including the resin, must be physically measured. Stress in the actual composite is then obtained by dividing "P_ϵ" by the measured area of the actual composite.

PREPARED BY:	NORTH AMERICAN AVIATION, INC.	PAGE NO. OF
CHECKED BY:	Figure 1	NA-63-1358-13 REPORT NO.
DATE:	COMPOSITE STRESS-STRAIN CURVE CONSTRUCTION	MODEL NO.



NOTATION: σ_w = STRESS IN WIRE AT STRAIN ϵ

σ_c = STRESS IN COMPOSITE AT STRAIN ϵ

σ_s = STRESS IN SHEET AT STRAIN ϵ

σ_{cyp} = YIELD STRESS OF COMPOSITE AT STRAIN ϵ_{yp}

K = RATIO OF STRESS IN SHEET TO STRESS IN WIRE - σ_s/σ_w

A_c = CROSS SECTIONAL AREA OF COMPOSITE = $A_s + A_w$

A_w = CROSS SECTIONAL AREA OF WIRE

A_s = CROSS SECTIONAL AREA OF SHEET

p = RATIO OF WIRE AREA TO COMPOSITE AREA - A_w/A_c